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SHIP RESPONSE SENSITIVITY TO FORECAST AND
MEASURED WAVE SPECTRA

by

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and

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SHIP PERFORMANCE DEPARTMENT

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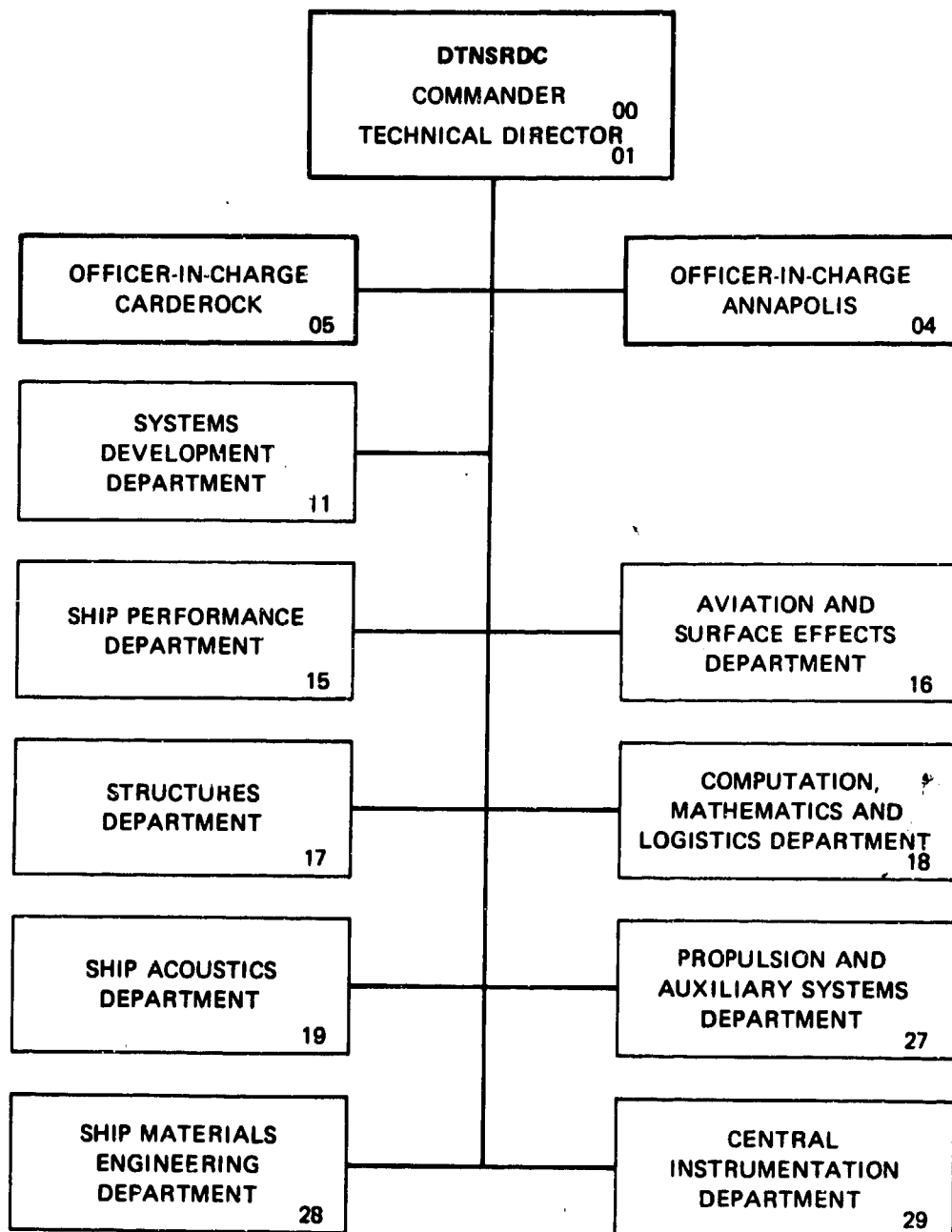
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Ship HNLMS TYDEMAN, which is relatively short and beamy. Comparisons of predicted and measured ship response are given in the frequency domain. Significant values derived from spectra are also compared. The quantity of measured data for correlation is limited; but agreement of the SOWM forecast waves with measured waves is not completely satisfactory. The ability to predict realistic ship response is also tenuous for the ship HNLMS TYDEMAN. The geometry of that ship is near the limits of that permitted by the ship motion strip theory encapsulated in SMP80. For pitch and heave motions, the forecast response spectra show inadequate agreement with measured response spectra and could provide unreliable indicators of ship performance. Roll, which is a narrow-banded process, is fairly insensitive to the correlation between the forecast and measured waves in the cases examined. For those cases, peak frequency always matched between forecast and measured roll response. Sample wave forecast and measurement comparisons are also provided for a routine North Atlantic transit of the Dutch container ship MV HOLLANDIA.

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NOTATION

RAO_Z	Heave response amplitude operator (meter/meter) ²
RAO_{ZB}	Vertical displacement at the bow response amplitude operator (meter/meter) ²
RAO_θ	Pitch response amplitude operator (degree/meter) ²
$S_Z(\omega_e)$	Heave response spectral density, meter ² -second
$S_{\ddot{Z}}(\omega_e)$	Heave acceleration response spectral density, G ² -second
$S_{ZB}(\omega_e)$	Vertical displacement at the bow response spectral density, meter ² -second
$S_\zeta(\omega)$	Wave spectral density, meter ² -second
$S_\theta(\omega_e)$	Pitch response spectral density, degree ² -second
$S_\phi(\omega_e)$	Roll response spectral density, degree ² -second
U	Wind speed, knots
$(\tilde{Z}_a)_{1/3}$	Heave significant response, meters
$(\tilde{\ddot{Z}}_a)_{1/3}$	Heave acceleration significant response, G's
$(\tilde{Z}_{Ba})_{1/3}$	Vertical displacement at the bow significant response, meters
$(\tilde{\zeta}_w)_{1/3}$	Significant wave height, meters
$(\tilde{\theta}_a)_{1/3}$	Pitch significant response, degrees
$(\tilde{\phi}_a)_{1/3}$	Roll significant response, degrees
μ	Ship heading, degrees
ω	Wave frequency, radians/second
ω_e	Wave encounter frequency, radians/second

ABSTRACT

This study presents some preliminary investigations on calculating ship response by using the Spectral Ocean Wave Model (SOWM) for wave inputs to SMP80, the Navy's Standard Ship Motion Prediction Program. This technique could be a valuable tool for design and operations by providing a measure of ship response in specific conditions and over requested routes. The ship used to develop the motion responses was the Dutch oceanographic research ship HNLMS TYDEMAN, which is relatively short and beamy. Comparisons of predicted and measured ship response are given in the frequency domain. Significant values derived from spectra are also compared. The quantity of measured data for correlation is limited; but agreement of the SOWM forecast waves with measured waves is not completely satisfactory. The ability to predict realistic ship response is also tenuous for the HNLMS TYDEMAN. The geometry of that ship is near the limits of that permitted by the ship motion strip theory encapsulated in SMP80. For pitch and heave motions, the forecast response spectra show inadequate agreement with measured response spectra and could provide unreliable indicators of ship performance. Roll, which is a narrow-banded process, is fairly insensitive to the correlation between the forecast and measured waves in the cases examined. For those cases, peak frequency always matched between forecast and measured roll response. Sample wave forecast and measurement comparisons are also provided for a routine North Atlantic transit of the Dutch container ship MV HOLLANDIA.

ADMINISTRATIVE INFORMATION

The work reported herein was carried out at the request of the Fleet Numerical Oceanography Center (FNOC) and the Naval Sea Systems Command (NAVSEA). It was authorized by FNOC Work Request WR-50110 and the Surface Wave Spectra for Ship Design Program, which is funded under Project Number 62759N and Block Number SF-59-557-695. It is identified by the Work Unit Numbers 1-1568-833-01 and 1-1500-300-19, respectively, at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC).

INTRODUCTION

The Navy's increasing interest in seakeeping has required a more accurate understanding of the marine environment. The waves that influence ship motions are one ingredient of the "Input-Output" approach developed by St. Denis and Pierson

in their theory of linear superposition of ship motions.^{1*} The understanding and verification of the theory prompted ship designers to find a means of using this predictive tool to impact the ship design process by producing seaworthy vessels more able to perform their missions in a seaway. The marine environment has been generalized by the ship designer into sets of spectral families such as those defined by the Pierson-Moskowitz or the Bretschneider spectra. These families have been useful for developing response amplitude operators (RAO's) in the controlled setting of tank model experiments and design analytic investigations. However, the use of spectral families has failings from an operational standpoint by lacking specificity for a location. Under pressures of economics, safety, and operations, those providing operational guidance to ships at sea have a need for better real-time representation of the sea environment than provided by the idealized spectral families.

The Fleet Numerical Oceanography Center (FNOC), in Monterey, California, has implemented a numerical prediction program which is a spectral model of ocean waves in all phases of growth and decay. Entitled "The Spectral Ocean Wave Model (SOWM)," the program, originally developed by Professor Willard J. Pierson and his associates,² computes two-dimensional (15 frequencies by 12 directions) wave spectra, using a modified Phillips-Miles growth mechanism.^{3,4} Wave energy is propagated between approximately 2000 grid points spaced up to 180 nautical miles throughout the Northern Hemisphere. The grid points are arranged on an icosahedral-gnomonic projection allowing great circles to be represented as straight lines within a projected triangle, thus wave energy which propagates along great circle routes can be handled in a simple mathematical fashion. In the operational mode, the model is used in making computations and analyses twice daily using three-hour time steps and forecasts out to 72 hours. A new prediction of the directional wave spectrum is made for each time step at each grid point. Using the conditions at the previous time step, the energy propagated into the grid area from distant storms, and the driving wind from the pressure field, the model updates the spectrum for the new time step. The SOWM does not explicitly model any nonlinear wave, wind, or current interaction effects.

One of the potential applications of wave spectral data forecast by SOWM is Optimum Track Ship Routing (OTSR). It has been demonstrated that OTSR saves the U.S. Navy 4.5 million dollars per year by minimizing fuel consumption during transit,

*A complete listing of references is given on page 19.

minimizing ship damage in storm areas, and increased reliability of ship's schedules.⁴ A potential improvement to the routing program could be the ability to accurately predict ship response to given wave conditions on a particular ship course. These ship responses would then be incorporated into the routing algorithm. Ships that respond differently to the existing conditions would have varying optimum routes that reflect the differences in dynamic responses.⁵

Of paramount importance to ship routing is the requirement to obtain an indicator of response that is simple and accurate. Given the number of ships that FNOC tracks daily, and the quantity of calculations required to develop optimum routes, a lengthy, complicated analysis of ship response is not reasonable. One approach is to use theoretical means of calculating a response spectrum. The response spectrum of a ship is calculated from the RAO's by multiplication with the wave spectrum in the encounter frequency domain. In the past, RAO's were calculated from model tests, but in the last decade computer-based prediction programs have successfully been applied to the calculation of RAO's. Combined with a numerical development of the prevailing waves such as the SOWM, a means of calculating the specific response of a vessel to a particular prevailing seaway may be possible. The ability to do this is strictly dependent upon the validity of the predicted RAO's, and upon the ability of the SOWM to reproduce the actual wave conditions. In routine ship routing, the use of response spectra to characterize response is not feasible due to the preponderance of data involved. To describe ship response in a more manageable form, the response spectra are reduced to significant* values eliminating the need to look at frequency domain data. However, even if predicted significant values are used to describe response, there must be confidence that they reflect reasonable agreement with measurement in the frequency domain. It could be misleading to have agreement of significant values when the predicted and measured response spectra indicate fundamentally different characteristics in the frequency domain.

The purpose of this study is to present preliminary investigations on calculating ship response by using the SOWM for the wave definition and SMP80, the Navy Standard Ship Motion Prediction Program. Comparisons are given in terms of spectra in the encounter frequency domain and significant values derived from the spectra.

*Significant values are defined as the average of the one-third highest amplitudes for ship responses and double amplitude for wave heights. It has been shown statistically that significant values can be derived from spectra and are approximated by the product $4 \times \sqrt{\text{spectral area}}$.

Also of interest in the investigation is the sensitivity of the response to differences (predicted to measured) in wave spectra. It is important to know the level of accuracy of wave prediction required to adequately predict response; perhaps exact agreement between measurement and prediction may not be required for realistic prediction of the ship motion. Some analysis of this accuracy requirement is provided in the current investigation.

SOURCE OF WAVE AND RESPONSE DATA

The measured ship response and measured wave data were gathered during full-scale trials of two Dutch vessels: the oceanographic research ship HNLMS TYDEMAN and the container ship MV HOLLANDIA. Principal dimensions of the TYDEMAN are given in Table 1.

In both trials, measurement of the prevailing sea conditions were taken by wave buoys developed at the Delft University Ship Hydrodynamics Laboratory. As summarized in Reference 6, the spherical buoy has a diameter of 0.43 m and is half immersed when floating. The buoy is stabilized by means of a light tubular construction of about 1 meter length, a thin steel wire connected to this extension, and a stabilizing weight. In a seaway the buoy follows the wave surface with sufficient accuracy, and the simple stabilizing system keeps the buoy within a few degrees of a vertical position. The buoy is equipped with an antenna and transmits a frequency modulated signal of the vertical acceleration to the ship. The vertical displacement is found by numerical double integration of the digitized acceleration recording. Digital data reduction methods have been used to compute the power density spectra of the wave recordings. The wave spectra derived from wave recordings will be referred to as measured spectra though it is clear that spectra are not measured directly. Only unidirectional wave spectra are used because the waves were measured with only a single buoy and directionality was not determined. However, visual observations of directionality were taken and were used to determine ship heading.

The spectra derived from the buoy measurements were compared to SOWM forecast spectra from FNOC transmitted to the ships via DTNSRDC. The SOWM wave forecasts were developed daily during the trials for 0000 and 1200 GMT and transmitted to the ships, primarily in parameterized form, once daily. In addition, during the TYDEMAN trials, response data were measured for heave, pitch, roll, and vertical displacement of the bow. Details of the trials and measurements are available in References

6, 7, and 8. One case of simultaneous response and wave measurement is available from the TYDEMAN trials. In addition, three other wave measurements are available from the TYDEMAN trials. Two wave measurements are available from the HOLLANDIA trials.

The following comparisons are shown:

1. Measured and forecast wave spectral densities.
2. Wave spectral densities of forecasted spectra at 0, 24, 48, 72 hours or TAU 0, TAU 24, TAU 48, TAU 72, respectively (TAU is the number of hours a forecast is projected into the future).
3. Forecasts for wind speed and significant wave height for 3 to 4 days preceding the trial data.
4. Response spectral densities for heave, pitch, roll, and heave acceleration.
5. Significant values of wave height and ship response derived from the predicted and measured spectra.

Past work at sea has resulted in a scarcity of good measured data and the same is true in this study. There are insufficient data for comparison to draw broad conclusions; therefore, the results presented here are only preliminary to the understanding of the prediction of operational ship response by theoretical means. More measured wave (including directionality) and response data are needed to establish the validity of the approach.

WAVE AND RESPONSE COMPARISONS

The ship speed for all comparisons is 9 knots.

Case 1. On 16 March 1978 HNLMS TYDEMAN was conducting trials near 58°30' N 12°00'W. During these operations both wave and ship response data were measured. The ship's track during the trial followed an arrow shaped pattern, see Figure 1, that allowed response data collection in quartering, bow, beam, head, and following sea conditions. Figure 2 shows the wave spectral density measured during each run of the trial and corresponds to each run on Figure 1. Table 2 details the environmental conditions prevailing during each run. The spectra show good steady-state conditions with no radical changes in characteristics. However, there is a wave component at a wave frequency of 0.4 rad/sec that shows some decay. Figure 3 shows a comparison of wave spectral densities for measured waves during the TYDEMAN trials and the SOWM forecasts for the nearest time and location. It is clear that the forecast densities fall well below those derived from measurements. The forecast is made for TAU 0,

meaning it is same day, present conditions and should be the most accurate estimate of the prevailing wave conditions. The significant wave heights derived from the measured data are 5.7 and 4.7 m at 0815 and 1330 GMT, respectively. The forecast significant wave height of 3.6 m is notably lower than either of these. Figure 4 shows SOWM forecasts made on succeeding days that are projected to the same day, that is 16 March 1978 at 1200 GMT and TAU 0. If precise forecasts were possible, then all three curves on Figure 4 would be identical; however, because the wind fields become more accurate as the forecast day is approached, the TAU 0 forecast should be the most realistic. But, forecast TAU 48 wave spectral densities on Figure 4 agree better with the measurements of Figure 3 than the TAU 0 forecasts. This is also reflected in the significant values shown in Figure 5 where forecasted significant wave height and wind speed are compared to the measured significant wave height and wind speed. On 16 March, it can be seen that the measured values taken on the TYDEMAN trial show good agreement with significant wave height and wind speed forecast at TAU 48, that is at 12 GMT, 14 March. The reasons for this are not clear though the trend has been noticed in other cases. The better agreement of TAU 48 forecast may not be true in all SOWM forecasts.⁹ The TAU 0 cases should reflect the best SOWM prediction, therefore, the points are connected by a broken line on Figure 5.

Figures 6 to 10 present the response spectral densities against wave encounter frequency derived from application of the wave spectra of Figure 3. Heave acceleration is also developed but does not include a comparison with a measurement from the TYDEMAN. Figure 6 shows pitch response comparisons. The "TYDEMAN Measured" curve reflects the actual data gathered during the trial; the "Forecast" curve is response developed from SOWM forecast waves and SMP80 RAO's; the "DTNSRDC Calculated" curve is response developed from measured waves and SMP80 RAO's; the "DELFT Calculated" curve is the response developed by the Ship Hydrodynamics Laboratory, Delft University which was responsible for the TYDEMAN trials and data reduction.⁷ The Delft RAO's are generated by a ship motion program similar to SMP80. From Figure 6, it is seen that comparisons are poor between the measured, forecast, and calculated pitch spectra. While the measured response spectrum shows a peak at the same frequency (e.g., 0.8 rad/sec) as the calculated one, it is much smaller and has a secondary peak at 0.4 rad/sec. In addition, the nature of the forecast response spectrum is different than either the calculated or measured curves. The reason for this is not clear though it is possible that a swell wave of about 0.4 rad/sec was present though not forecast by the SOWM. Comparison of the significant responses derived from the spectra vary from 3.3 degrees for the forecast, 4.1

degrees for the measured and 5.0 for the calculated. It should also be noted that differences in the spectra may be due in part to the fact that long-crested (unidirectional) waves were assumed. The forecast spectrum, however, indicates some spreading (e.g., ± 60 degrees) about the primary direction. The long-crested assumption is inherent in all response comparisons of the report.

Similar results are shown in Figure 7 for heave response and vertical displacement of the bow, see Figure 8. The natures of the measured, forecast, and calculated heave responses are very different. The forecast heave response falls well below the calculated curve and, as in pitch, the measured response shows a strong component at 0.4 rad/sec. No measured data were available for heave acceleration; however, Figure 9 does show the calculated and forecast responses. Again, the spectral comparisons are not favorable and the significant values do not agree well.

Roll spectral response comparisons are given in Figure 10. In this case, the forecast and calculated (DTNSRDC) results show good comparison with a peak at a wave encounter frequency of 0.7 rad/sec. However, these results are very different from the measured roll response which is much lower and peaks at 0.55 rad/sec. The good agreement of the forecast to calculated roll response is attributed to the narrow-banded response of roll from SMP80. Over the wave frequencies that roll responds, the forecast wave spectral density agrees with the measured wave spectral density, e.g., see Figure 3 at 0.7 rad/sec. With matching input and identical transfer functions the predicted responses must agree. It is also noted that the long-crested assumption is apparently not very critical to roll prediction in this case, though the prevailing seas must have been short-crested since rolling in head seas and pitching in beam seas did occur, see Reference 6. The poor agreement of the measured data in all modes with either the calculated or forecast cases needs further investigation.

Figure 11 shows the pitch RAO's that were calculated by SMP80 and the pitch RAO's derived from the TYDEMAN measurements by assuming long-crested seas. The measurement-derived RAO's show similar characteristics over some of the wave encounter frequency range ($\omega_e \geq 0.55$ rad/sec) though generally falling below the calculated RAO's. However, at the lower frequencies there is a significant deviation from the SMP80 prediction showing a large peak at 0.35 rad/sec. This deviant peak appears again in both the heave RAO, Figure 12, and the vertical displacement at the bow RAO, Figure 13. Comparisons over the rest of the frequency range are

also poor. The calculated RAO's from SMP80 have been evaluated with comparisons to model experiments and are generally valid for moderate to heavy wave conditions. Figure 12 raises a question of the reliability of the measured responses from the TYDEMAN trials. Such problems with full-scale data analysis are common. It is difficult to derive accurate full-scale RAO data due to short-crested sea conditions, since they cannot yet be measured routinely from ships.

The large RAO component at 0.35 rad/sec wave encounter frequency indicates excessive response measured without proportionate measurement in the waves. The wave frequency component of approximately 0.3 rad/sec transfers to a wave encounter frequency at 9 knots of 0.35 rad/sec. From Figure 2, the measured waves at the encounter frequency of 0.3 rad/sec show good repeatability and steady-state conditions.

At the present time, this case (16 March 1978) provides the only measured data available to the authors for comparison. In the examination of other cases, measured response data are not available. Therefore, comparisons are done with the responses calculated by SMP80. It is assumed that the RAO's from SMP80 are a fair representation of ship dynamics and are a good filter for the input waves. The RAO's should affect the forecast and measured waves in similar ways; therefore, the output response will reflect differences in input wave spectra and provide a good measure of merit in predicting ship response.

Case 2. On 8 December 1978 the HNLMS TYDEMAN was on trials near 38°00'N 25°00'W. Figure 14 shows the comparison of the wave spectral densities from the measurements from the trials and the forecast data from SOWM. The measured wave data portrays a rapidly varying situation. The two measured spectra were taken 25 minutes apart, and there was a 151 degree wind shift of constant strength. The two spectra are very different with the latter being lower. At higher frequencies (0.45 rad/sec and above) the measured spectra are similar; however, the change in the peaks indicates unsteady conditions. This makes comparison to the forecast waves difficult due to the inability of the SOWM to model rapid weather changes (i.e., frontal conditions, hurricanes, localized storms).^{*} In spite of this, the forecast waves are not unreasonable when compared to the 1455 GMT measurement. The peak is shifted to the right (0.42 rad/sec) but the shape is similar and the significant wave height is comparable (7.5 to 7.3 m).

^{*}This is largely due to the large grid point spacing and the 12 hour time intervals between forecasts.

A comparison of the SOWM forecast waves, Figure 15, projected to the same day shows surprisingly good agreement. There is one component at TAU 48, 0.35 rad/sec wave frequency, that seems out of line but agrees over the remaining frequencies. The general agreement is reflected in Figure 16 which shows forecasts of wind speed and significant wave height. On 8 December 1978 there is a grouping of significant wave heights near 7.5 m, with good agreement to the measured significant wave height. The point to be made is that while the significant wave heights show reasonable comparison, the wave spectra may not.

The examination of responses furthers this point. Figures 17 through 21 give the response spectra for pitch, heave, vertical displacement at the bow, heave acceleration and roll. For each, the RAO's are generated from SMP80; both available measured and SOWM forecast spectra are used to predict response spectra. An examination of pitch, see Figure 17, shows responses from measured data comparing well in spite of the fact that the measured waves change so drastically over 25 minutes. The pitch responses from forecast waves do not compare favorably with the others, even though significant wave height comparisons are reasonable. This can be explained by examination of the frequencies over which pitch responds, i.e., wave encounter frequencies greater than 0.6 rad/sec, see Figure 11. In this frequency range (accounting for frequency transformation), the measured wave spectra show close agreement while the forecast wave spectrum is higher as shown by Figure 14. The opposite is true in heave response, see Figure 18. Here the responses follow the wave spectra trends. The forecast heave acceleration response, Figure 20, shows similar trends to the forecast pitch response. The comparison of roll response, Figure 21, shows all cases responding at exactly the same frequencies. The reason is the very narrow-banded character of RAO's for roll. The forecast response for roll shows the maximum response, because the encountered forecast wave spectrum more closely aligns with the natural period of roll.

This case seems to indicate that if reliable pitch prediction is desired, then the measured and forecast waves must show agreement in the higher frequencies. The opposite is true for heave response where wave agreement is needed in the lower frequencies.

Case 3. On 10 December 1978 the HNLMS TYDEMAN was on trials near 44°34'N 19°16'W. From this trial only wave measurements are available. Figure 22 shows the comparison of SOWM forecast wave spectra to measured wave spectra. Again two measurement times are presented and, as in the previous case, the conditions are varying. The

measured significant wave height drops from 6.2 m to 5.4 m over 25 minutes, and the wind varies in speed and direction from 27 knots, 170 degrees to 36 knots, 135 degrees. Above a wave frequency of 0.65 rad/sec the three spectra are similar; however, the SOWM forecast spectrum contains significantly greater energy over the middle frequencies. In addition, the measured spectra show a characteristic double peak which the forecasts miss completely. This is obviously a swell component present in the prevailing conditions. Figure 23 shows fairly diverse predictions for the SOWM forecasts projected to the same day. The TAU 0 case has a higher peak and likewise greater significant wave height. This is reflected in Figure 24 which presents forecast and measured significant wave heights and wind speeds. On 10 December the measured data fall below the forecast TAU 0, but one of the measured points shows agreement with TAU 24 and TAU 48. Also the forecast significant wave heights are increasing on 10 December as the day is approached.

The responses from 10 December 1978 are given on Figures 25 to 28. Examining pitch, Figure 25 shows the SOWM forecast response spectra larger than the measured response spectra. However, neither show the double peak that so typified the measured wave spectra because the pitch RAO does not respond to the lower frequencies where one of the peaks in the wave spectra existed. The pitch agreement is slightly better than the previous case. Heave, on the other hand, given in Figure 26, displays very different measured and forecast responses. Due to the unity value RAO's of heave at low frequencies, Figure 12, all of the wave energy is transferred through to the response. The divergence of the two measured cases points to the importance of having good wave agreement at lower frequencies to adequately predict heave response. The heave acceleration response, Figure 26, shows trends similar to pitch; both of which are dependent upon good agreement of wave spectra, forecast to measured, for higher frequencies. Relative to other motions, the roll response, given in Figure 28, agreement is good. The peaks are exactly together and significant values are similar.

Case 4. On 12 December 1978 the HNLMS TYDEMAN was on trials near 48°17'N 8°41'W. From this trial only wave measurements are available. This trial took place in a higher sea state than other cases as shown by Figure 29 which compares measured and SOWM forecast wave spectra. The forecast wave spectrum contains much more energy with a peak at wave frequency 0.32 rad/sec and a significant wave height of 13.76 m. The measured significant wave height is 9.1 m, and the two spectra show good agreement at wave frequencies of 0.5 rad/sec and above. The measured wave spectrum peaks

at 0.5 rad/sec and is lower than the forecast waves at frequencies below 0.5 rad/sec. Comparisons of the SOWM forecasts projected to the same day are given in Figure 30 (TAU 24 is not available). There is a continued growth of the wave spectra as the day (TAU 0) is approached. This is reflected in Figure 31 of significant wave heights and wind speeds where the forecast significant wave height increases on 12 December. The measured significant wave height shows best agreement with forecast TAU 48; however, comparing the spectra from Figures 29 and 30 shows differing characteristics in the frequency domain. The forecast wave spectrum TAU 48 peaks at a wave frequency of 0.32 rad/sec and the measured wave spectrum peaks at 0.50 rad/sec. The comparison of forecast significant wave height for TAU 0 with the measured significant wave height is poor.

The comparison of pitch response spectra, Figure 32, shows better agreement. The SOWM forecast pitch response displays a slightly broader response than the measured. The measured pitch response spectrum falls below the forecast response spectrum at wave encounter frequencies below 0.6 rad/sec though significant values are similar. Comparison of heave response, Figure 33, does not provide satisfactory results and mirrors the disagreement of the wave spectra. The SOWM forecast heave response spectrum overpredicts the measured response by a factor of 10 at the peak which is not at the same frequency as the measured spectrum. The two, however, do agree at wave encounter frequencies above 0.6 rad/sec. The comparison of heave acceleration response, Figure 34, provides similar results as pitch. The roll response comparison is quite good, see Figure 35. The forecast roll and the measured roll spectra peak at the same frequency and show similar spectral shapes.

Again, as in the preceding cases, good prediction of pitch (and heave acceleration) is dependent upon good agreement of measured and forecast wave spectra in the higher wave encounter frequencies above 0.5 rad/sec. Heave requires wave spectra agreement at lower frequencies below 0.6 rad/sec. Roll is fairly insensitive to the level of agreement in the wave spectra and gives good response comparison.

Case 5. On 1 January 1979 the MV HOLLANDIA, a Dutch container vessel, conducted full-scale seakeeping trials on a normal service voyage of the ship from Northern Europe to the Caribbean. The ship was located at approximately 46°N 24°W. The purpose of the trial was to investigate the feasibility of a computer based ship-board monitoring and prediction system to ensure safe and economic ship operation.⁸ Wave measurements were made during the voyage in a manner similar to those taken

during TYDEMAN trials and with the same type of disposable wave buoy. Again, SOWM forecasts were provided by FNOC via DTNSRDC. The wave data, forecast and measured, is used as input to TYDEMAN RAO's to predict TYDEMAN responses to the seaway experienced by the HOLLANDIA. TYDEMAN responses are presented for evaluation, not HOLLANDIA response. Had HOLLANDIA ship lines been available, that ship's responses would also have been presented.

The comparison of the wave spectral density for measured and forecast waves, Figure 36, is typical of trends in the previously discussed TYDEMAN cases. The SOWM forecast and HOLLANDIA measured wave spectra show very different conditions. The forecast waves underpredict the severity of the conditions and miss the obvious peak sensed by the buoy. The measured wave spectra reflect steady-state conditions with the peak at a wave frequency of 0.6 rad/sec and a smaller peak at 0.3 rad/sec. The smaller peak appears to be a decaying swell. Figure 37 presents the comparison of the SOWM forecasts projected to the same day, while the comparison of HOLLANDIA measurements and SOWM forecasts for wind speed and significant wave height is given in Figure 38.

Once again the comparisons of the TYDEMAN response data using measured and forecast wave spectra show the application of the SOWM forecasts for real time calculation of ship spectral response to be questionable. In pitch, Figure 39, the forecast falls well below the measured response, and the significant values do not indicate this difference. Again, the two measured responses indicate good agreement even though the wave spectra differ at lower frequencies. If the SOWM forecast spectra could provide good resolution at the higher frequencies, then a benefit in predicting pitch response is possible. The opposite message is suggested by the heave response, Figure 40. The forecast response spectrum is well below the measured and peaks at a different frequency. The measured spectra show the importance to heave of good wave spectral agreement at the lower frequencies. Here there is strong divergence of the two measured heave responses due to the differences in the measured wave spectra at low frequencies. It is clear that pitch is more tolerant of wave spectral differences at low frequencies and heave is more tolerant of differences in high frequencies. Figure 41 shows heave acceleration and provides similar trends to the pitch case. The roll response, Figure 42, shows the forecast matching the peak very well though falling below the spectral densities. Still, roll response is not as dependent as heave and pitch upon good agreement of forecast and measured wave spectra.

Case 6. The final case is for 4 January 1979 when the MV HOLLANDIA was located at approximately 30°N 46°W. From this trial only wave measurements are available. The wave data, see Figure 43, are similar to the previous HOLLANDIA case with the SOWM forecast falling below the measured waves. There is a better matching of the peak location at wave frequency of 0.6 rad/sec. The measured data again show a decaying swell at a wave frequency of 0.3 rad/sec. The comparison of SOWM forecasts projected to the same day, see Figure 44, is typical of earlier cases. The TAU 0 and TAU 48 match with significant wave heights of 4.65 m and 4.79 m, respectively; yet, the TAU 24 case is much higher with a significant wave height of 6.44 m. The daily progression of significant wave height and wind speed, see Figure 45, shows some lack of correlation between measured waves and any of the forecasted waves.

The comparisons of TYDEMAN responses using the measured and forecast wave spectra repeat the previous trends, see Figures 46 to 49. Pitch, see Figure 46, and heave acceleration, see Figure 48, show some correlation over partial frequency ranges but miss the major peak of measured response of wave encounter frequency at 0.77 rad/sec. The forecast heave response correlation, Figure 47, is also lacking by falling well below the heave response derived from measured wave data and missing the low frequency values (0.35 rad/sec) altogether. The forecast significant values also are lower than the measured. Roll response is the only consistent candidate for good correlation. Figure 49 shows excellent agreement of the measured and forecast response with the significant values agreeing well. Again, roll response agreement seems to be relatively unaffected by poor correlation of wave spectral shape.

Throughout this section, it has been assumed that SMP80 provides a reasonable prediction of ship RAO's. This is generally true, however, the TYDEMAN, due to high length-to-beam ratio, may violate some of the strip theory assumptions of SMP80.

COMPARISON OF SIGNIFICANT VALUES

Figures 50 through 53 present the significant values of ship response plotted against the measured and forecast significant wave height. Two types of response data are shown:

1. Responses calculated using SMP80 and measured and forecast wave spectra.
2. Response measured from the 16 March 1978 TYDEMAN trial.

Due to the linear nature of the pitch and heave model in SMP80, these responses should increase linearly with increased wave height. Figures 50 and 51 generally

show pitch and heave to have a clear linear nature. However, the measured pitch and heave significant responses are generally less than the SMP80 data. The reason for this is the smaller valued RAO's derived from the measurements compared to the theoretically developed SMP80 RAO's; this is reflected in the pitch and heave RAO plots, Figures 11 and 12. Heave acceleration, see Figure 52, also shows linear response. Figure 53 shows a larger spread of responses for roll which is nonlinear in nature. Also, the measured roll response is much lower than the SMP80 generated response. This is explained by Figure 10 of roll response spectral density measured on the 16 March TYDEMAN trial. The measured roll response is much lower than both the SMP80 generated roll responses.*

A direct comparison of measured and forecast significant wave heights and response data is given as scatter diagrams, see Figures 54 through 58. Here the measured value is plotted against the forecast value and good prediction should produce points close to the diagonal. Figure 54 compares only wave height, while pitch, heave, heave acceleration, and roll are given in Figures 55, 56, 57, and 58, respectively. While the significant values do fall on either side of the diagonal, the limited number of data points prevent any broad conclusions. More measured ship response is required to verify the technique of predicting ship response from the SOWM forecast and SMP80 RAO's. To further quantify the correlation of SOWM forecast and measured data, error bands of 15 percent are assigned to the measured waves and response. If the SOWM forecast significant values fall within this 15 percent spread, then there is further support for the approach. Table 3 provides these comparisons. In the majority of the cases the 15 percent is not adequate for agreement. For those that do agree, the measured value just falls within the 15 percent spread. Again the drawing of conclusions is tentative.

Errors are likely to be present in both the forecast and predicted responses. For ship routing, it is important that there be good agreement for a given day. For ship design the error can be random over the long term. The small amount of data available here, see Figures 54 through 58, shows a random spread about the

*The process of developing RAO's from full-scale measurements is a difficult one at best. If the seas are long-crested then division of the response spectrum by the wave spectrum should provide the RAO for a given ship heading and speed. In practice, it is difficult to determine the ship speed, ship heading to the waves, and the directionality of the seas. It is very possible that poor estimates of these parameters contribute to some of the poor correlation reported herein. Wave directionality will be further discussed in a subsequent section.

diagonal. The conclusion that the significant values based on SOWM forecasts and assumed long-crestedness can be used operationally for ship response quantification is premature; especially in light of the poor agreement across the board of response spectra for all motions and cases presented here.

INFLUENCE OF DIRECTIONALITY

Remembering that the wave measurements during both the TYDEMAN and HOLLANDIA trials are in the form of point spectra and that the wave direction and spreading were estimated by the ships' officers, errors are probably introduced that can affect the predicted responses. Gerritsma and Beukelman⁷ investigated the influence of directionality and spreading upon their results. The study applied a cosine squared spreading function over an angular range of $\frac{\pi}{2}$ to $-\frac{\pi}{2}$, and four directions of the seaway were considered: 180, 165, 150, and 135 degrees (where 180 degrees is head seas). The directional wave spectrum, $S(\mu, \omega)$, is given as:

$$S(\mu, \omega) = f(\mu) S(\omega) \quad (1)$$

where $f(\mu)$ is the spreading function (for cosine squared spreading $f(\mu) = \frac{2}{\pi} \cos^2 \mu$ and for unidirectional seas $f(\mu) = 1$), and $S(\omega)$ is the wave spectrum at a point.

A matrix of various main directions of the seaway and spreading is examined for pitch and heave at the bow. Significant values of response are calculated using the measured waves as input to the DELFT ship motions program, and the results are presented in Table 4.⁵ The response spectra of the TYDEMAN are given in Figures 59 through 62, extracted from Reference 7. The results show that considerable corrections in wave direction and/or wave energy spreading function is needed to correct the significant values to the measured values. The results at $\mu = 135$ degrees and $f(\mu) = \frac{2}{\pi} \cos^2 \mu$ show better significant value agreement, but the agreement in the frequency domain for pitch and heave at the bow remains poor.

This large correction in seaway direction seems unreasonable but not out of the question; frequently, multidirectional seaways exist that could influence the results. In addition, there is little experimental support of the cosine squared spreading even though it is widely used to examine ship responses. It is feasible that the spreading function would have an asymmetric form, vary from location to location, and have a total angular spread of ≤ 90 or ≥ 90 degrees.⁹

This suggests that better agreement with the available data is not possible by resorting to idealize spreading such as cosine ± 90 degree model.⁷

CONCLUSIONS

1. The small amount of measured response and wave data is a real limitation to drawing conclusions on the usefulness of predicting ship responses via theoretical techniques with forecast waves and computed RAO's. More cases with other speeds are needed to confirm the technique for the TYDEMAN, and other ships should be evaluated to generalize the approach to all ships sizes and hull forms. Without simultaneous measurements of ship response and the prevailing seaway including directionality, the technique and its viability will always be in question.

2. The agreement of the SOWM forecast waves with the measured waves is less than satisfactory. In all cases, the wave spectral density of the forecast waves and measured waves differed to an unacceptable extent even though the winds seemed to be reasonably well input to the SOWM. The forecast waves were not consistent in over- or under-prediction and frequently the spectral shapes varied.

3. The ability to representatively predict ship responses from SOWM forecast waves and SMP80 RAO's is, as yet, not proven, at least for operational applications. For all motions, except roll, the forecast responses showed varying agreement with response spectra derived from measurement. From studies by Gerritsma and Beukelman,⁷ the problems are not caused by poor estimate of measured wave direction or by inability to quantify the spreading of wave energy.

4. The comparison of significant values with 15 percent error bands (Table 3) shows weak agreement; the majority of the modes do not qualify. This coupled with the poor frequency domain comparison raises doubts about the approach.

5. It is clear from the comparisons that the requirements of spectral resolution for heave and pitch prediction are different. Pitch motions require good wave forecasting at higher frequencies (for example, for the TYDEMAN above approximately 0.6 rad/sec wave frequency). Heave motions require good wave forecasting at lower frequencies (for example, for the TYDEMAN below approximately 0.8 rad/sec wave frequency). This is a consequence of the shape of the RAO's characteristic of each motion and may vary for varying hull forms and ship lengths.

6. Predicted roll characteristics differ from pitch and heave. Roll is fairly insensitive to the agreement shown between the forecast and measured waves. It is such a narrow-banded process that only the height of the response curve is affected

and the peaks of all the cases always match in frequency. It may be the best candidate for the technique, though more comparative data is needed to confirm this.

The above conclusions are based on a limited set of operational and forecast data. Wave directionality and the limits of ship motion theory (with regards to the TYDEMAN) may have effected these conclusions. While the application of SOWM to the development of representative ranges of ship response was demonstrated previously,⁹ this report examined the direct application of SOWM to real time (operational) calculations of ship response. Clearly, the subject requires further investigation. For purposes of ship routing, simple predictors of motion, applicable to generic operational functions (e.g., damage avoidance, fuel conservation, etc.) are required. It is considered that SMP80 provides reasonable RAO predictions for most naval combatants (e.g., lengths from 100 to 350 meters). However, the SOWM forecasts may require further refinement for real time response calculation.

The other area requiring additional work is in the application of response to improve operational decisions. The ship design and research communities have proposed several such methodologies⁵ and a method of determining motion levels which cause damage to FF-1052 Class frigates¹⁰ has also been introduced. For purposes of ship routing, the application of specific response levels may be difficult to achieve. Response limiting effects on mission performance are poorly quantified. Initially, the ship router may wish to only consider trends of ship response, e.g., increasing versus decreasing. Regardless, the topic at hand is of great interest to the Navy and will continue to be a subject of study at DTNSRDC.

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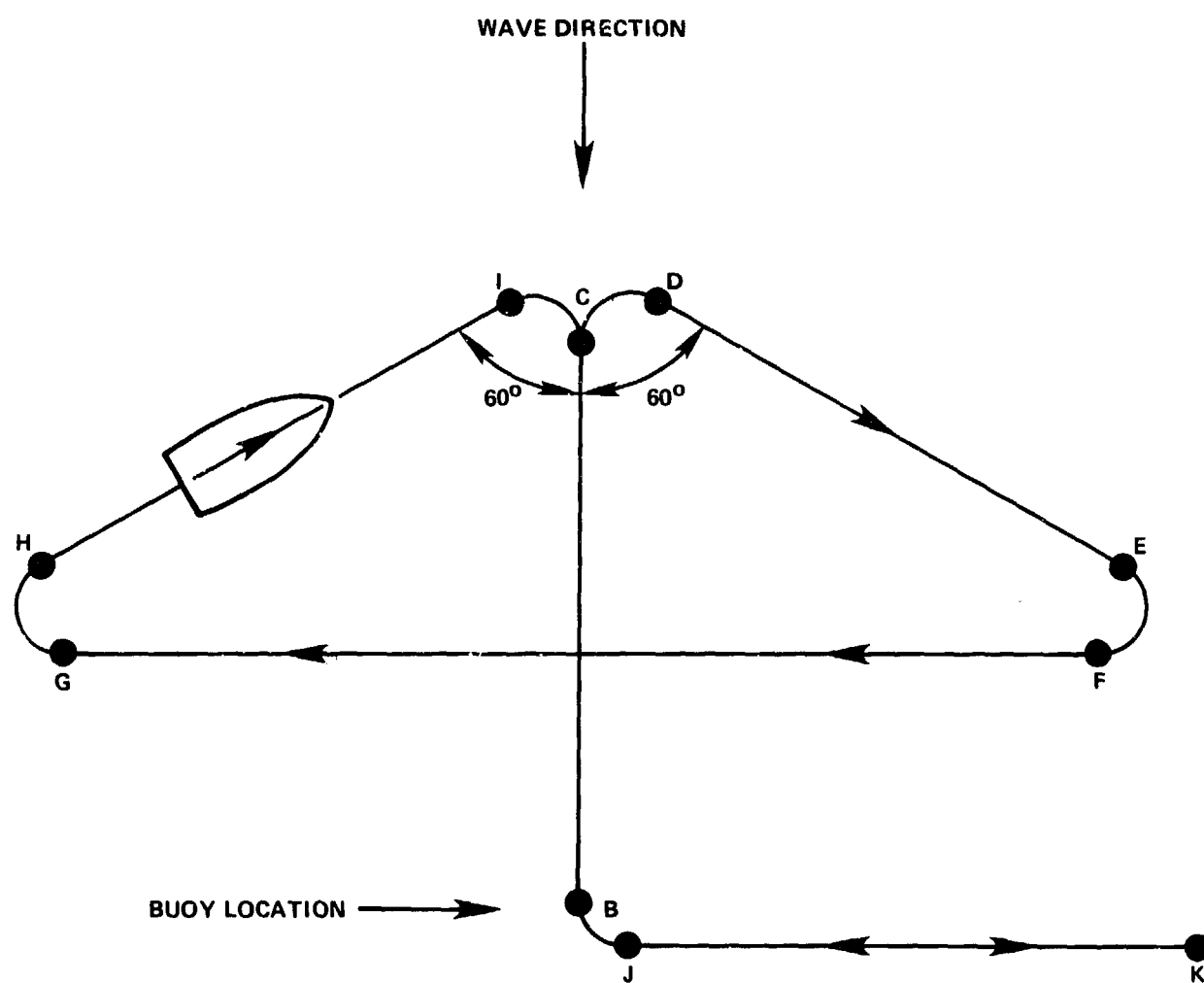


Figure 1 - TYDEMAN Trial Pattern

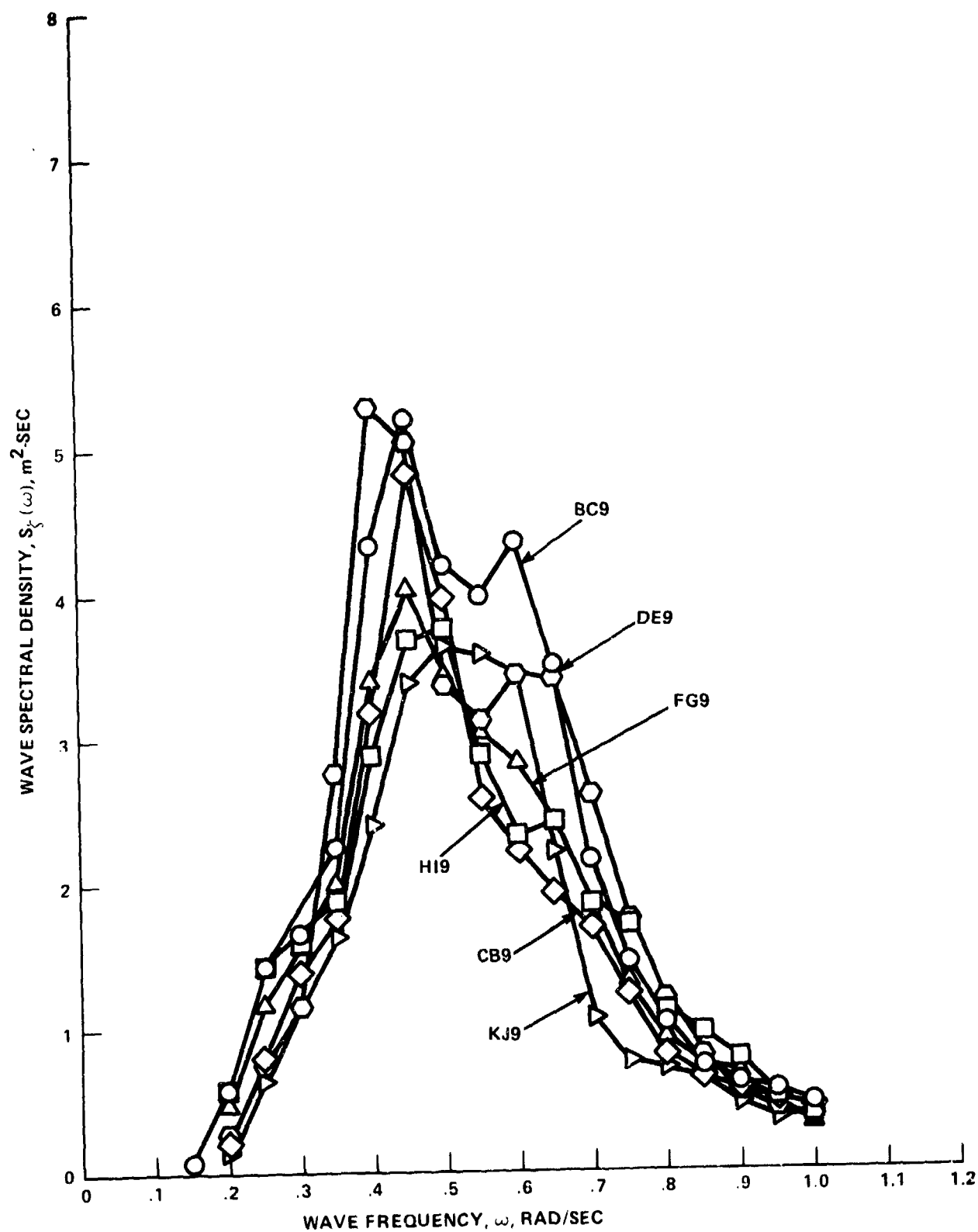


Figure 2 - Measured Wave Spectra - TYDEMAN Trials, 16 March 1978

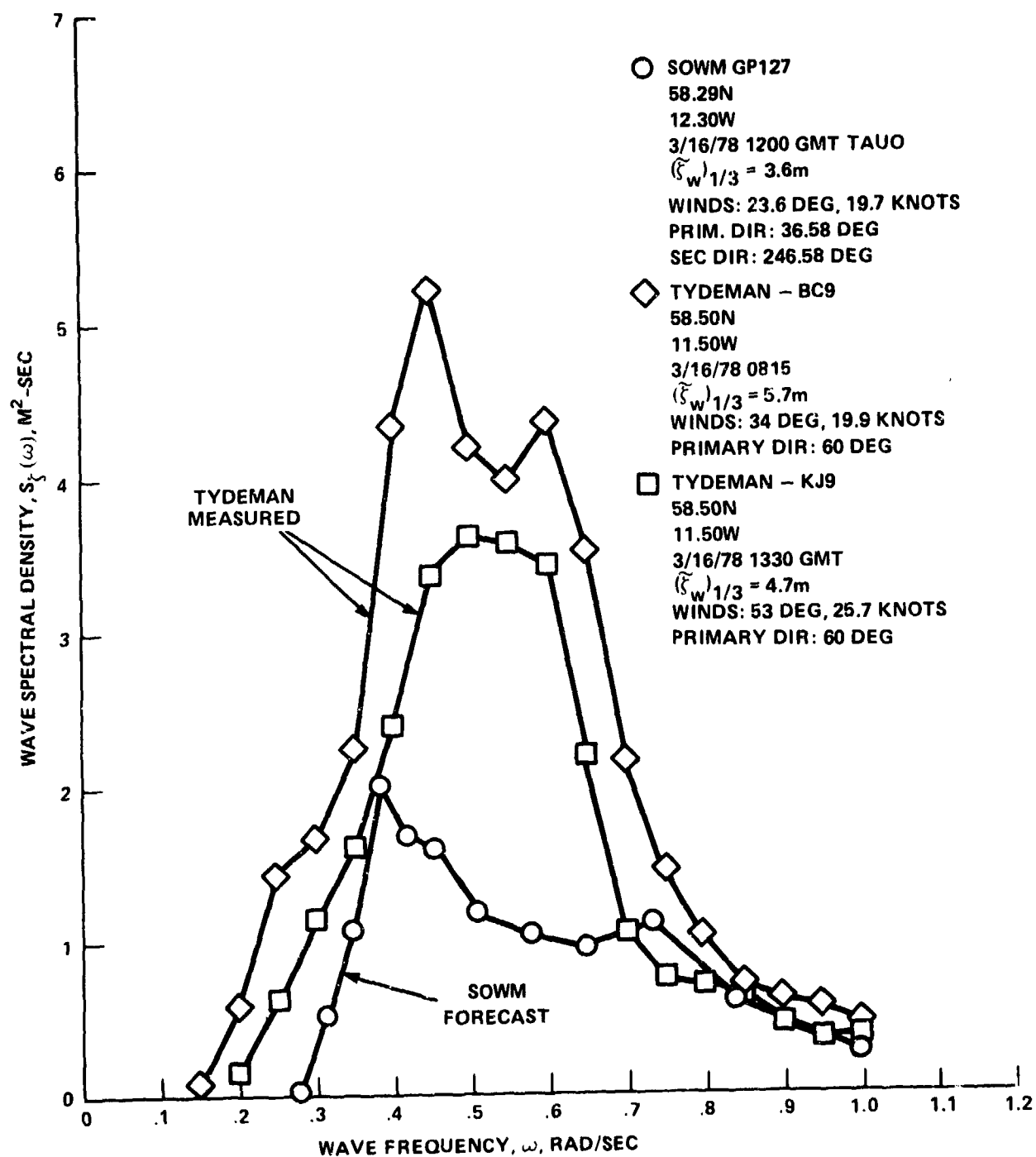


Figure 3 - Comparison Wave Spectral Density, Measured and Forecast - TYDEMAN Trials, 16 March 1978

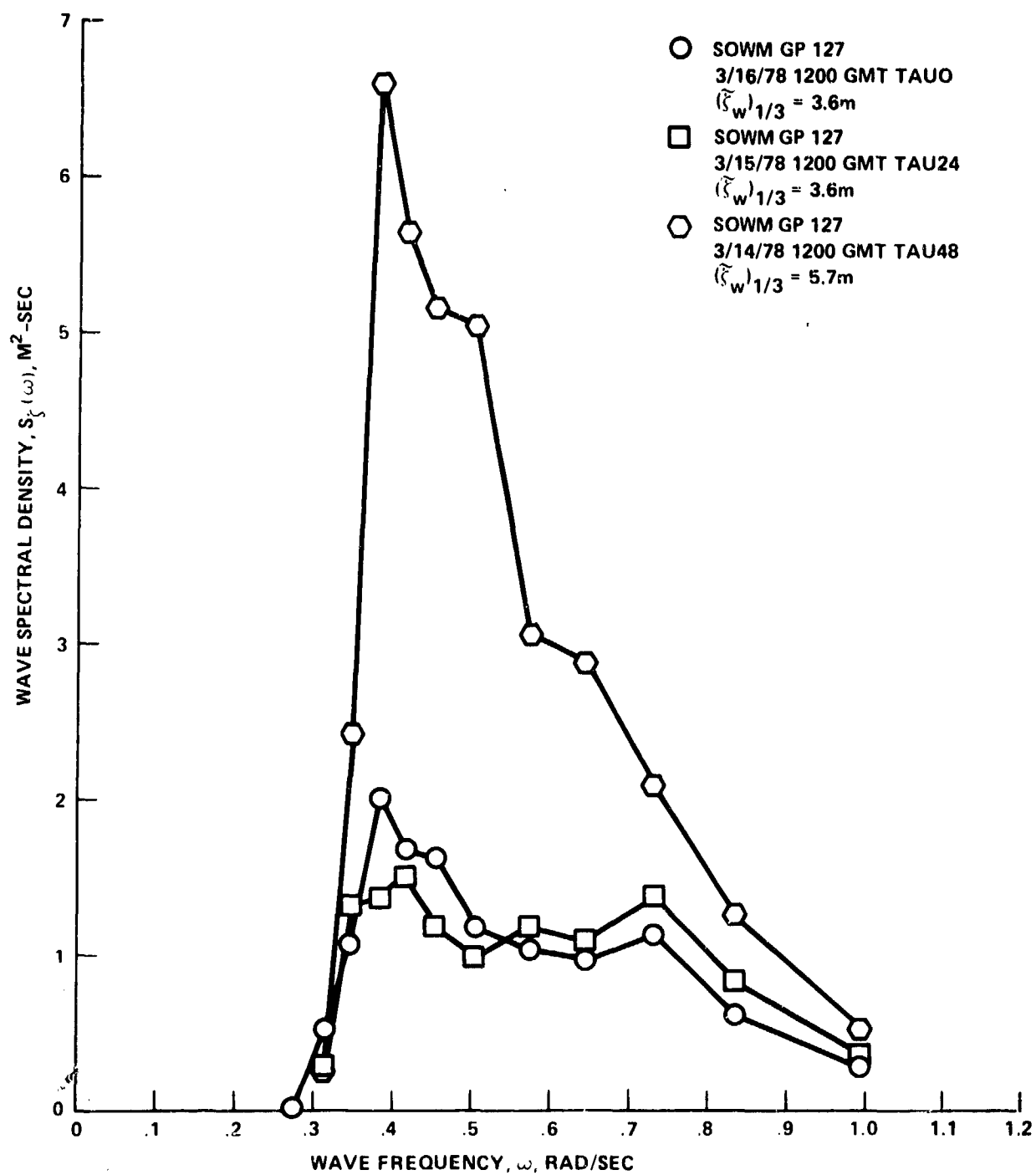


Figure 4 - Comparison of SOVM Forecasts Projected to Same Day -
TYDEMAN Trials, 16 March 1978

GP 127

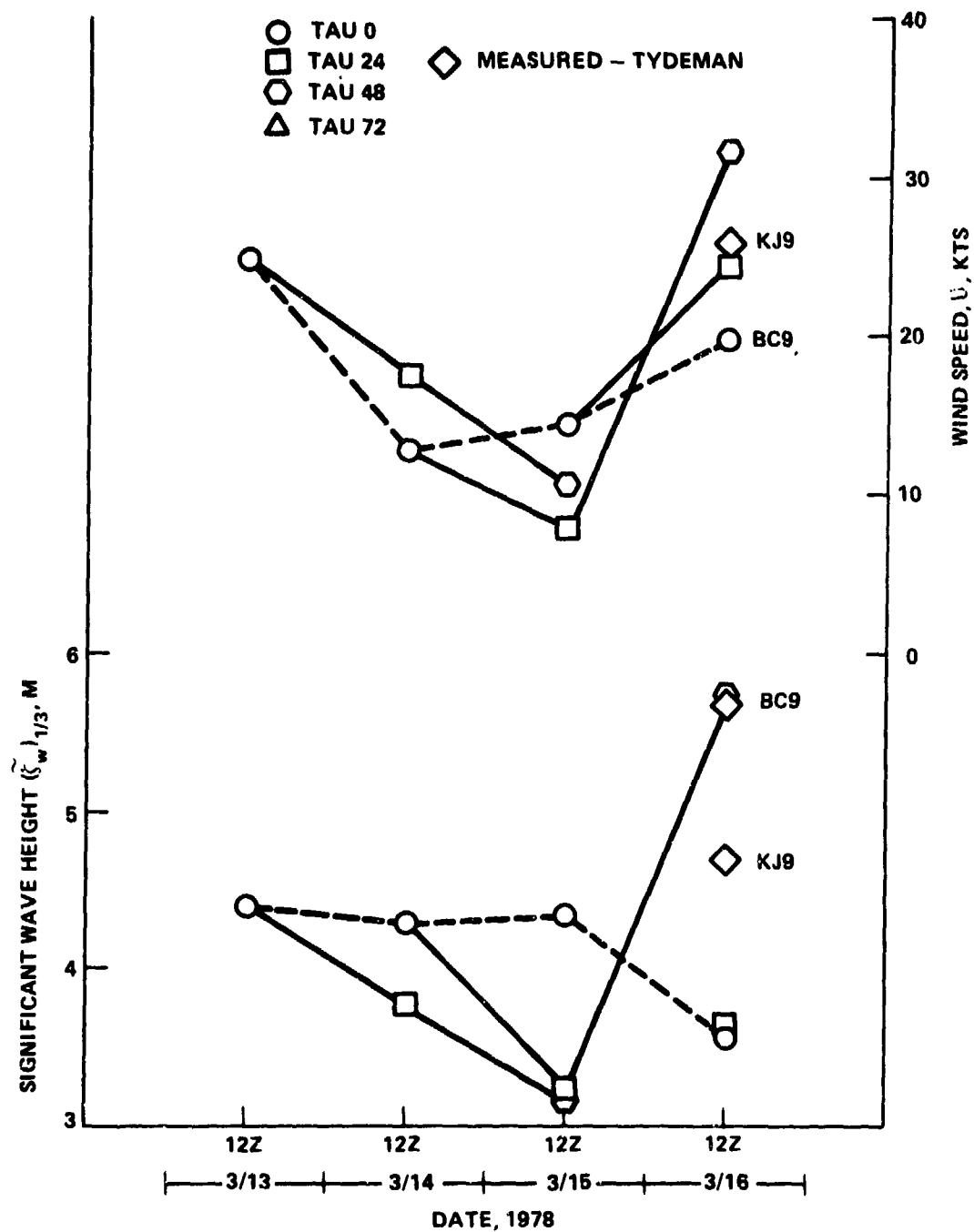


Figure 5 - Comparison of TYDEMAN Measurements and SOWM Forecasts for Wind Speed and Significant Wave Height, GP 127

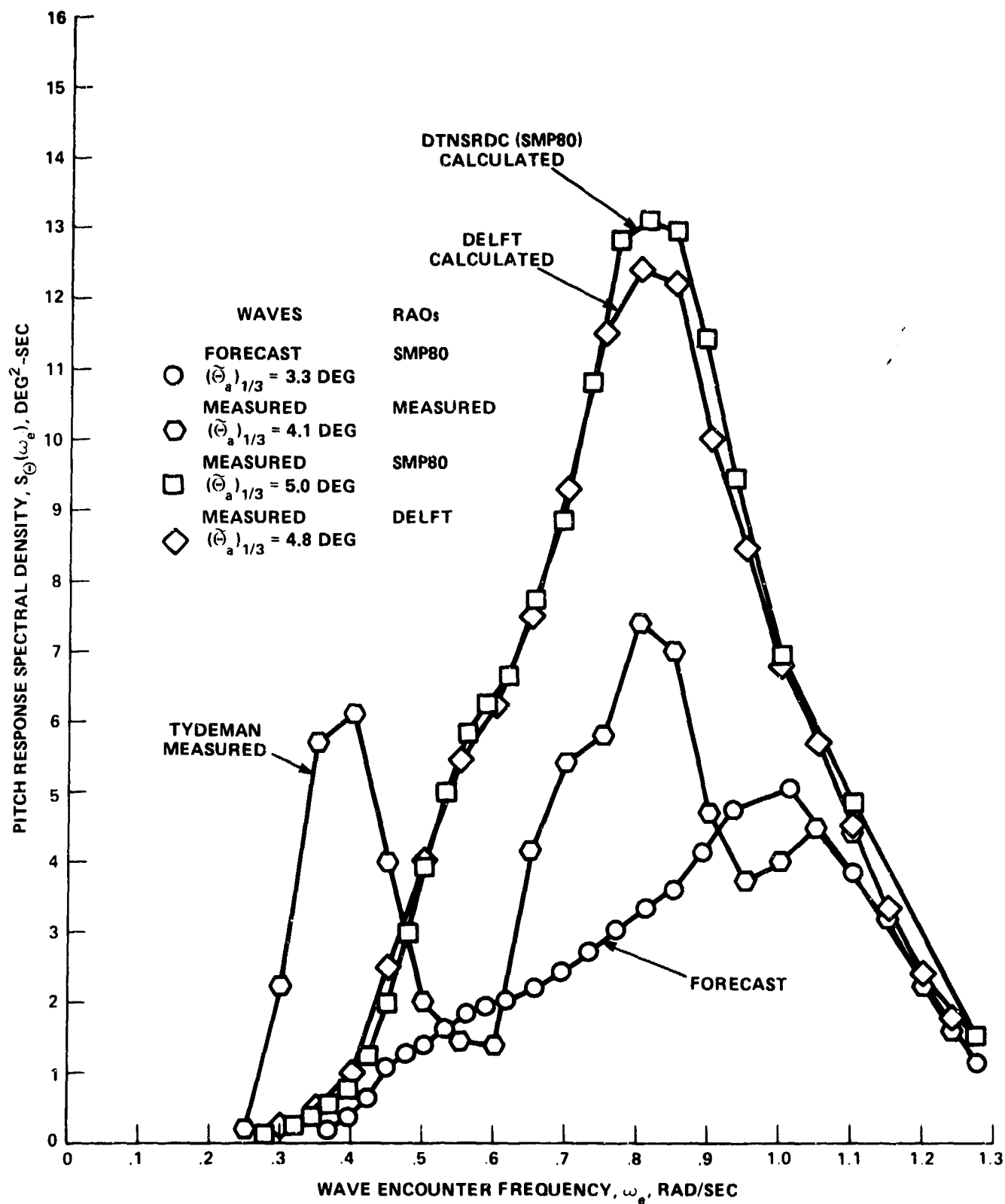


Figure 6 - TYDEMAN Pitch Response in Head Seas, 16 March 1978

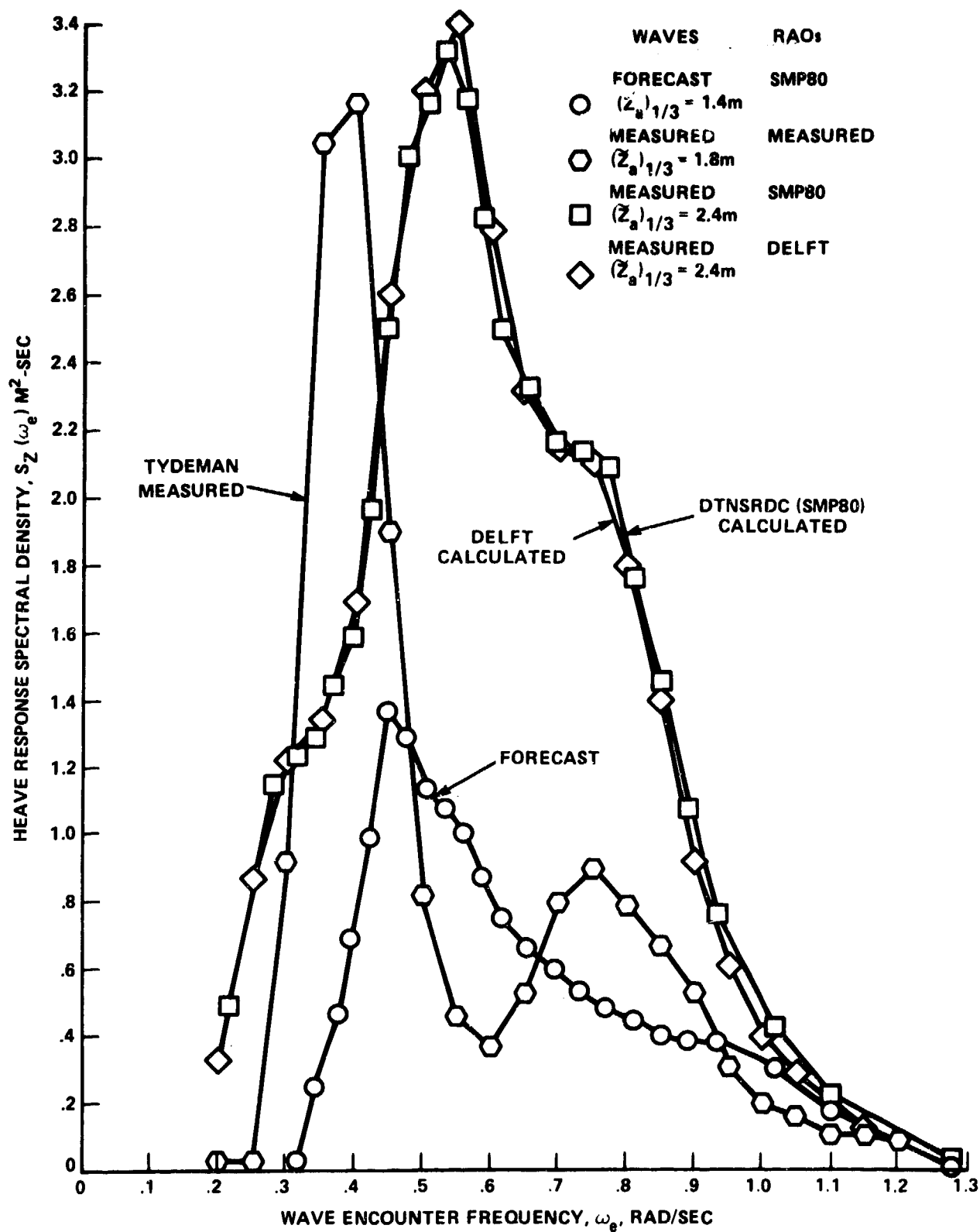


Figure 7 - TYDEMAN Heave Response in Head Seas, 16 March 1978

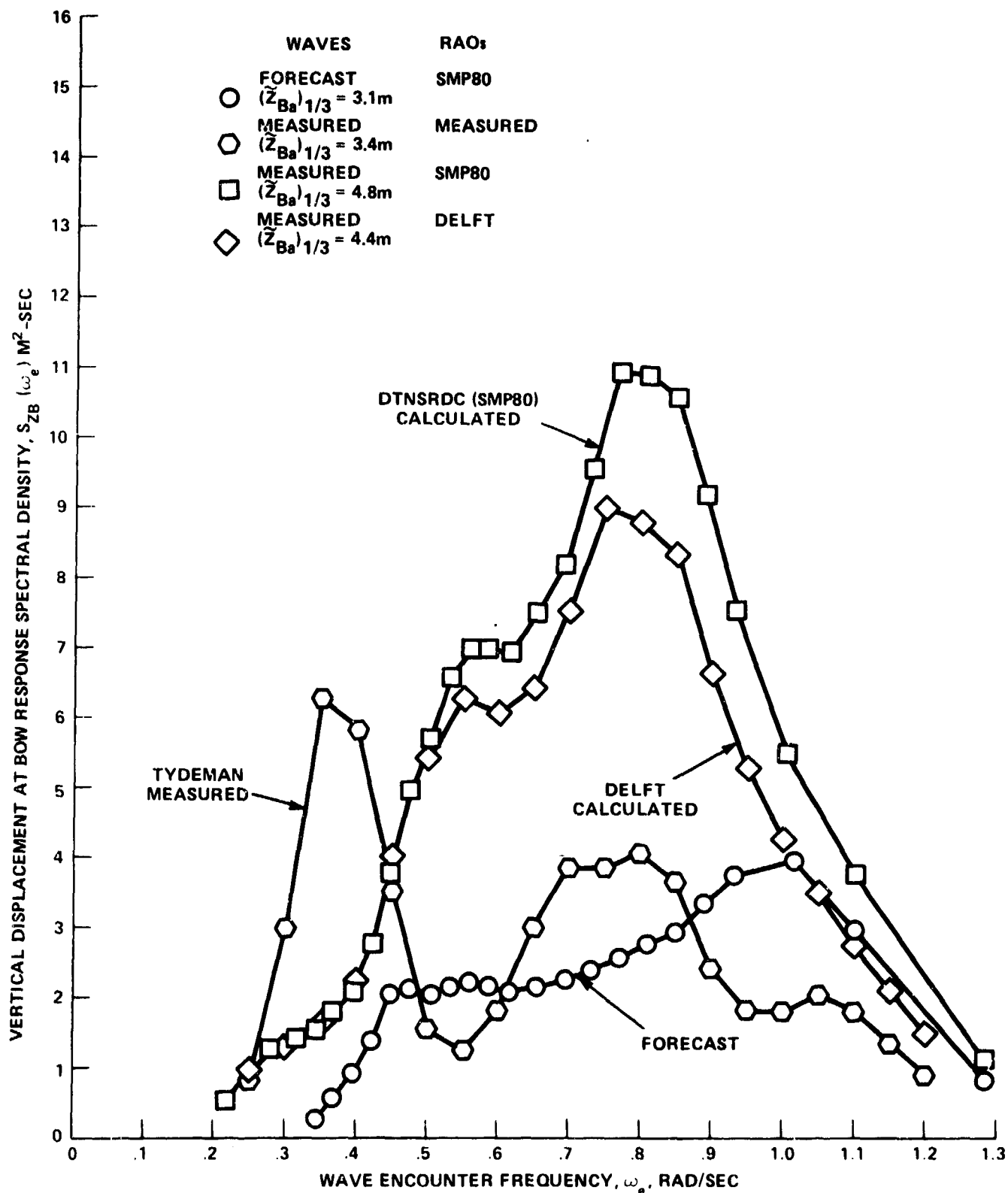


Figure 8 - TYDEMAN Vertical Displacement at the Bow Response in Head Seas, 16 March 1978

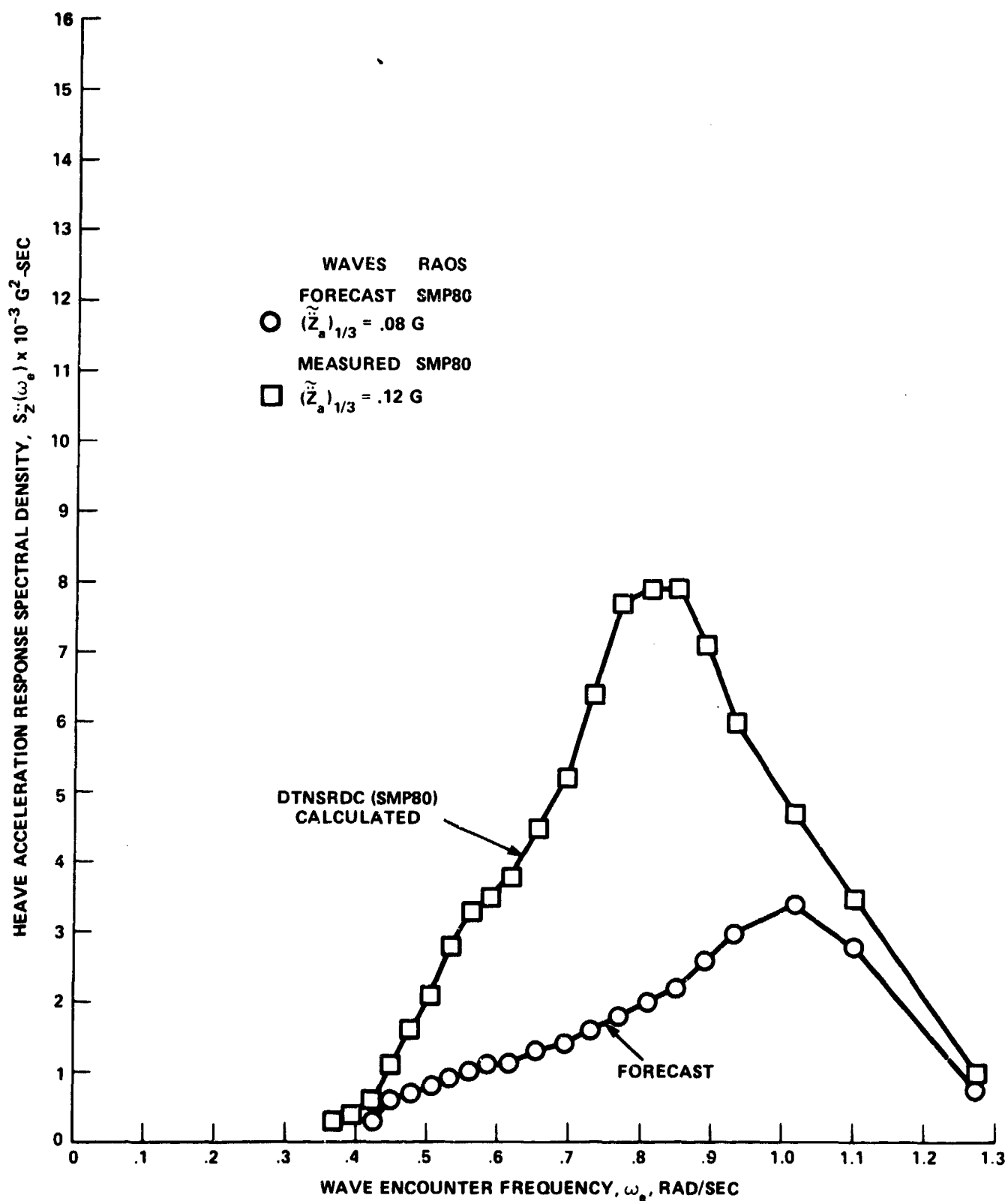


Figure 9 - TYDEMAN Heave Acceleration Response in Head Seas, 16 March 1978

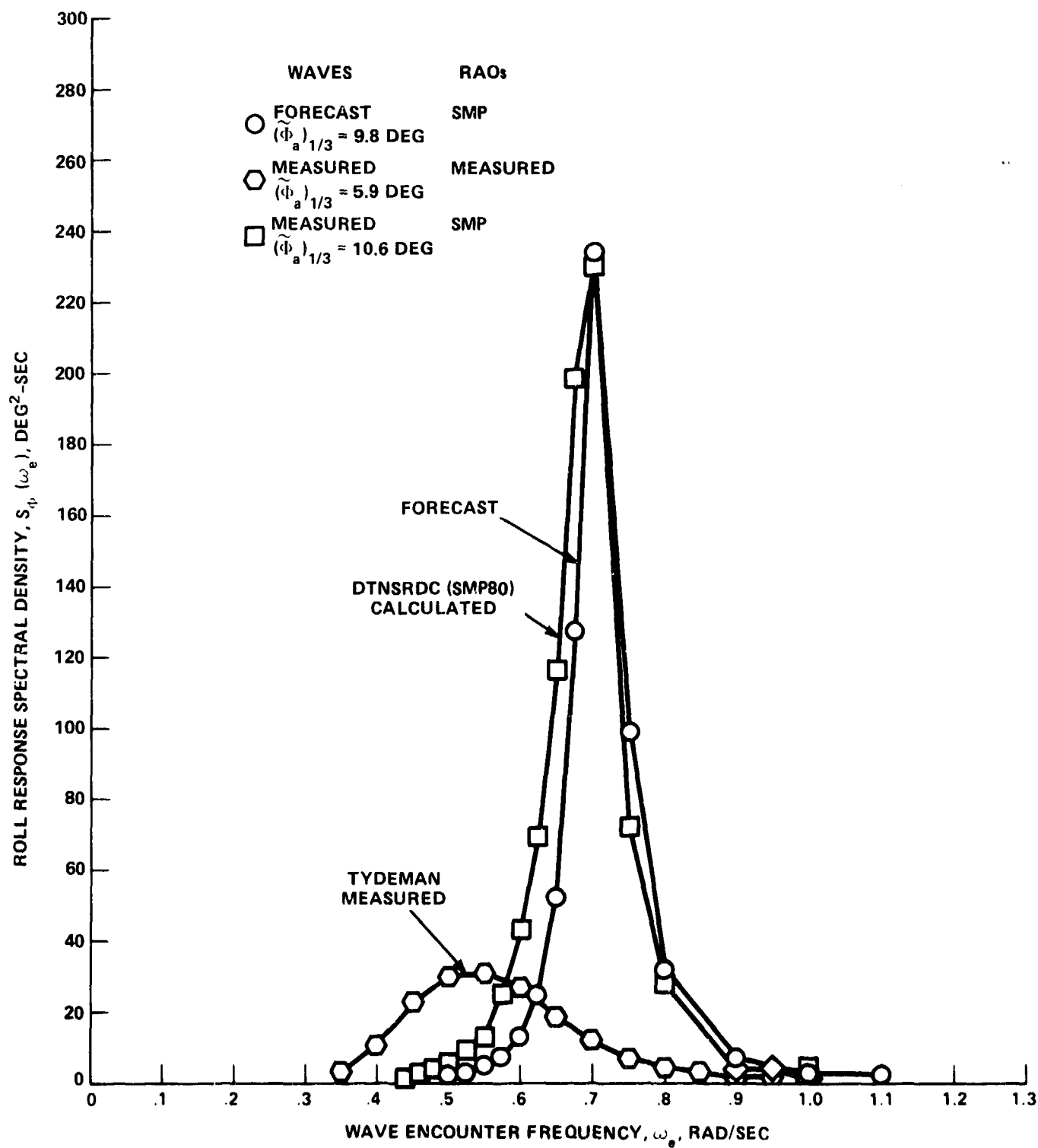


Figure 10 - TYDEMAN Roll Response in Beam Seas, 16 March 1978

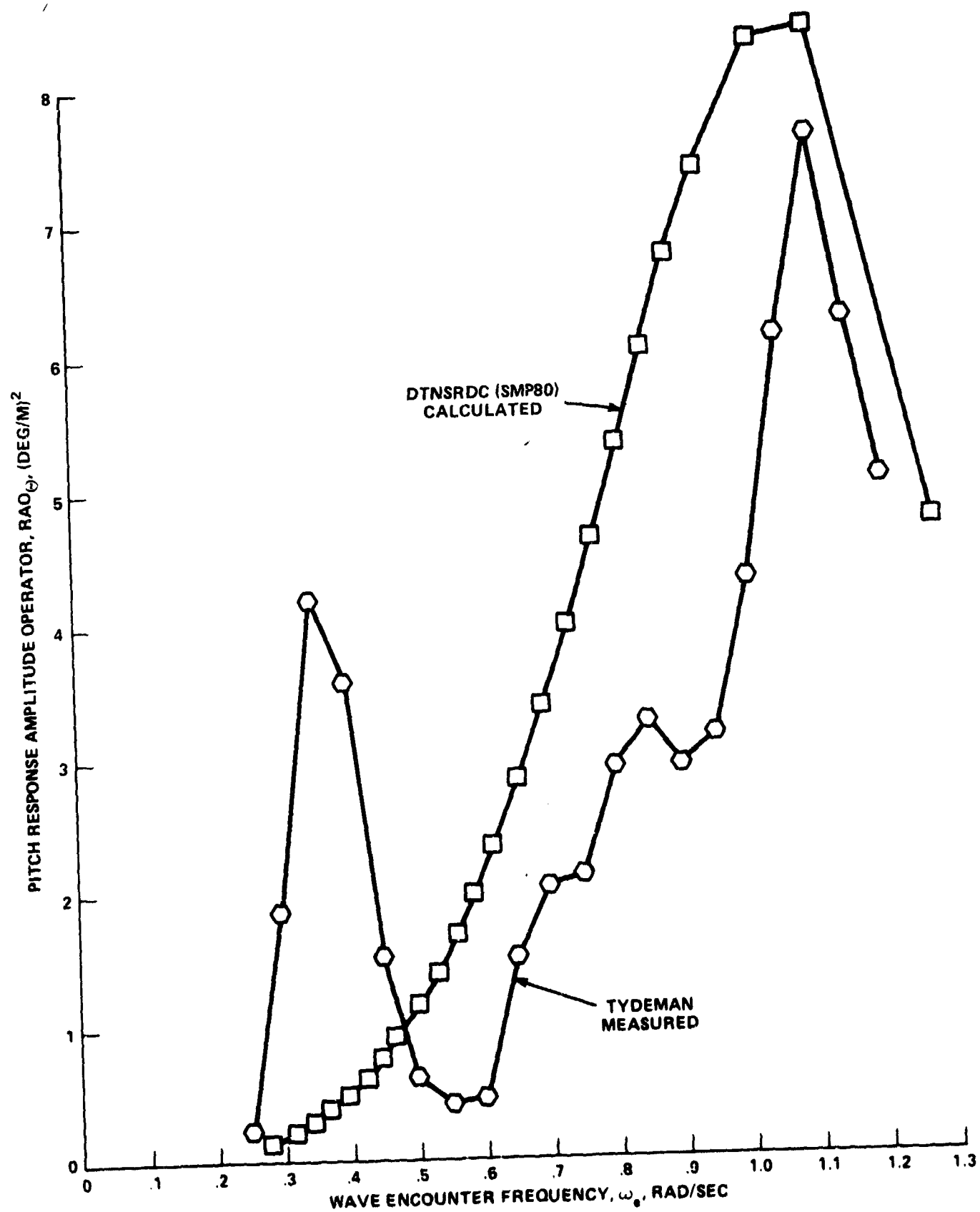


Figure 11 - TYDEMAN Pitch RAO's, Run BC9, 16 March 1978

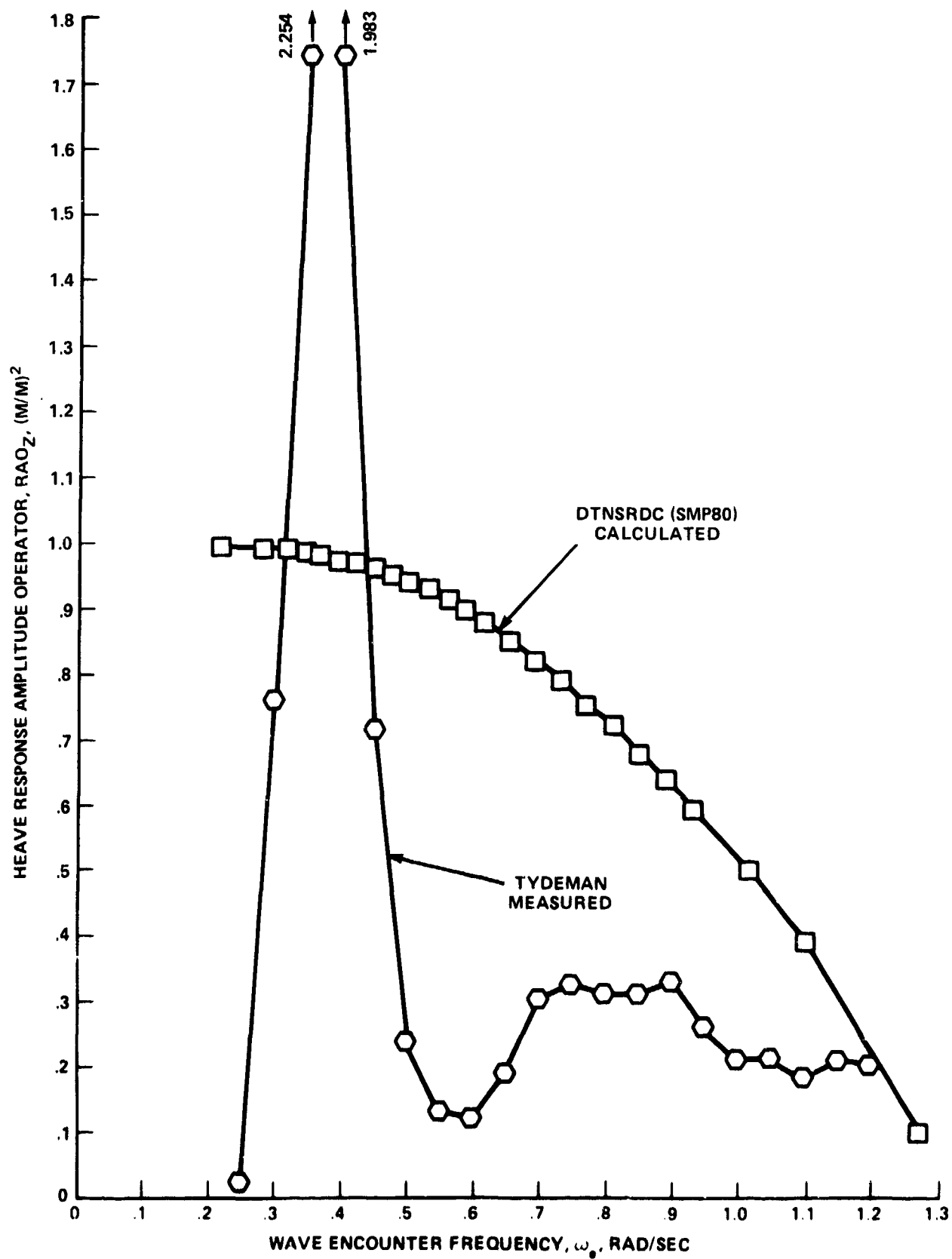


Figure 12 - TYDEMAN Heave RAO's, Run BC9, 16 March 1978

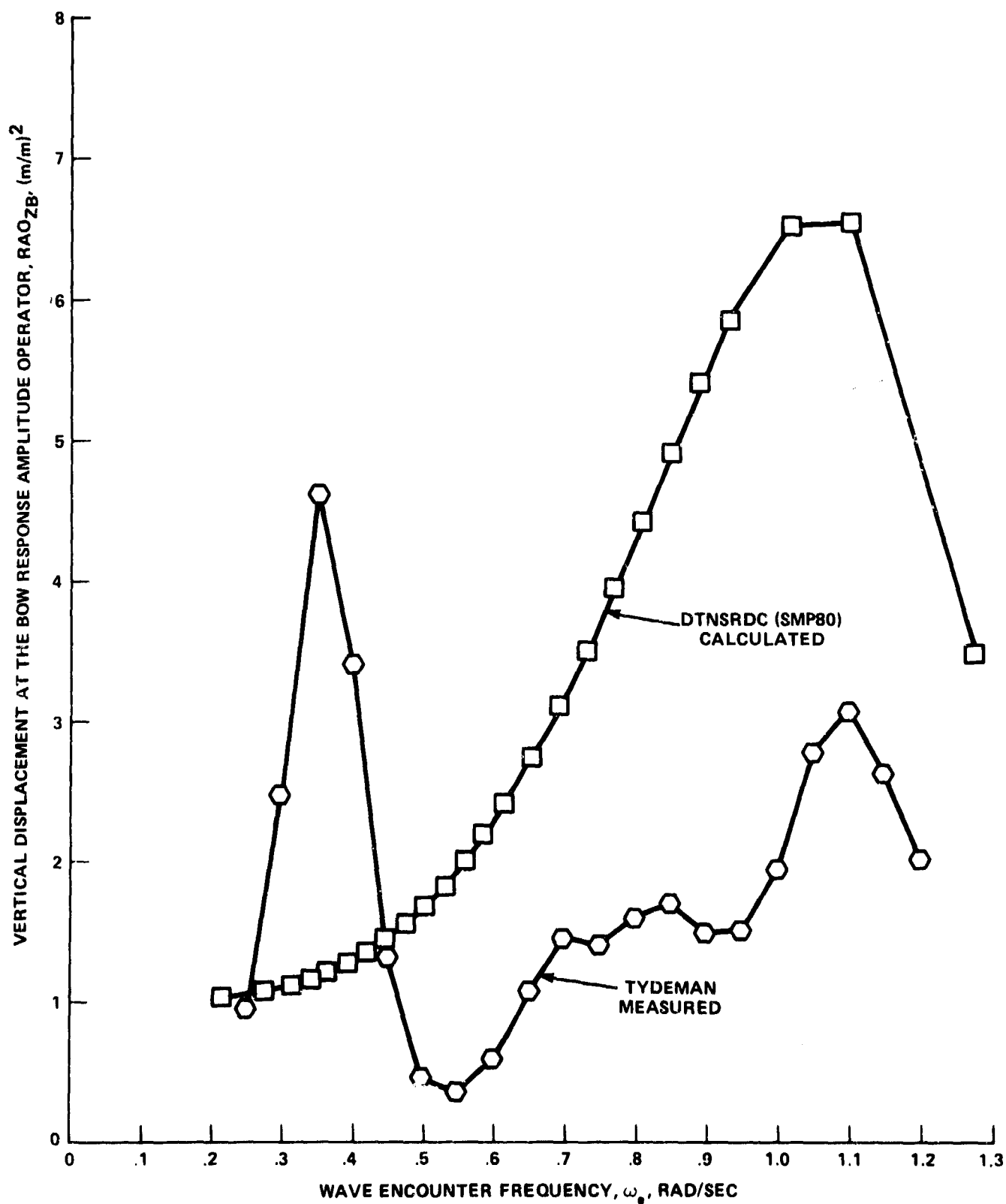


Figure 13 - TYDEMAN Vertical Displacement at the Bow RAO's, Run BC9, 16 March 1978

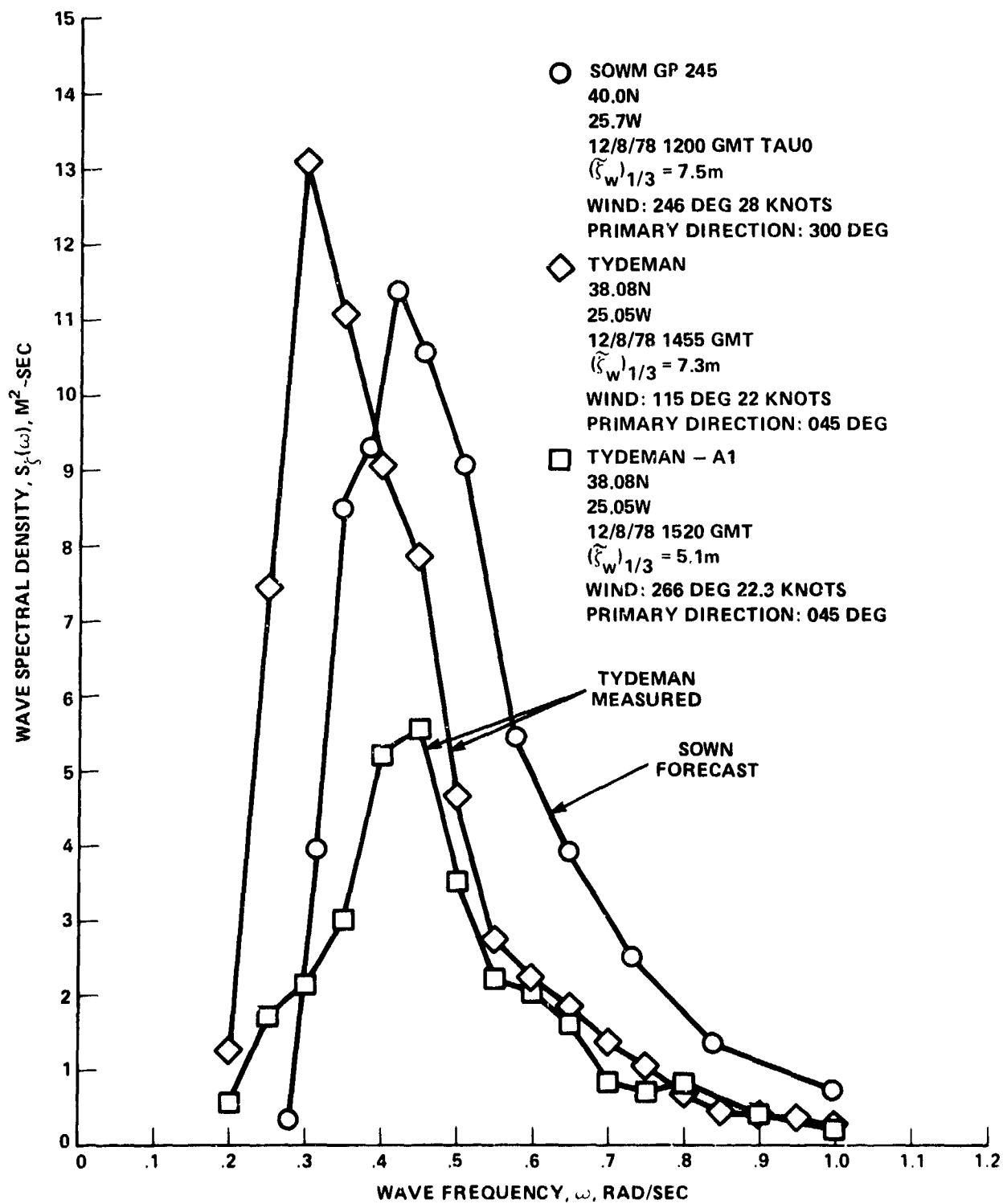


Figure 14 - Comparison Wave Spectral Density, Measured and Forecast - TYDEMAN Trials, 8 December 1978

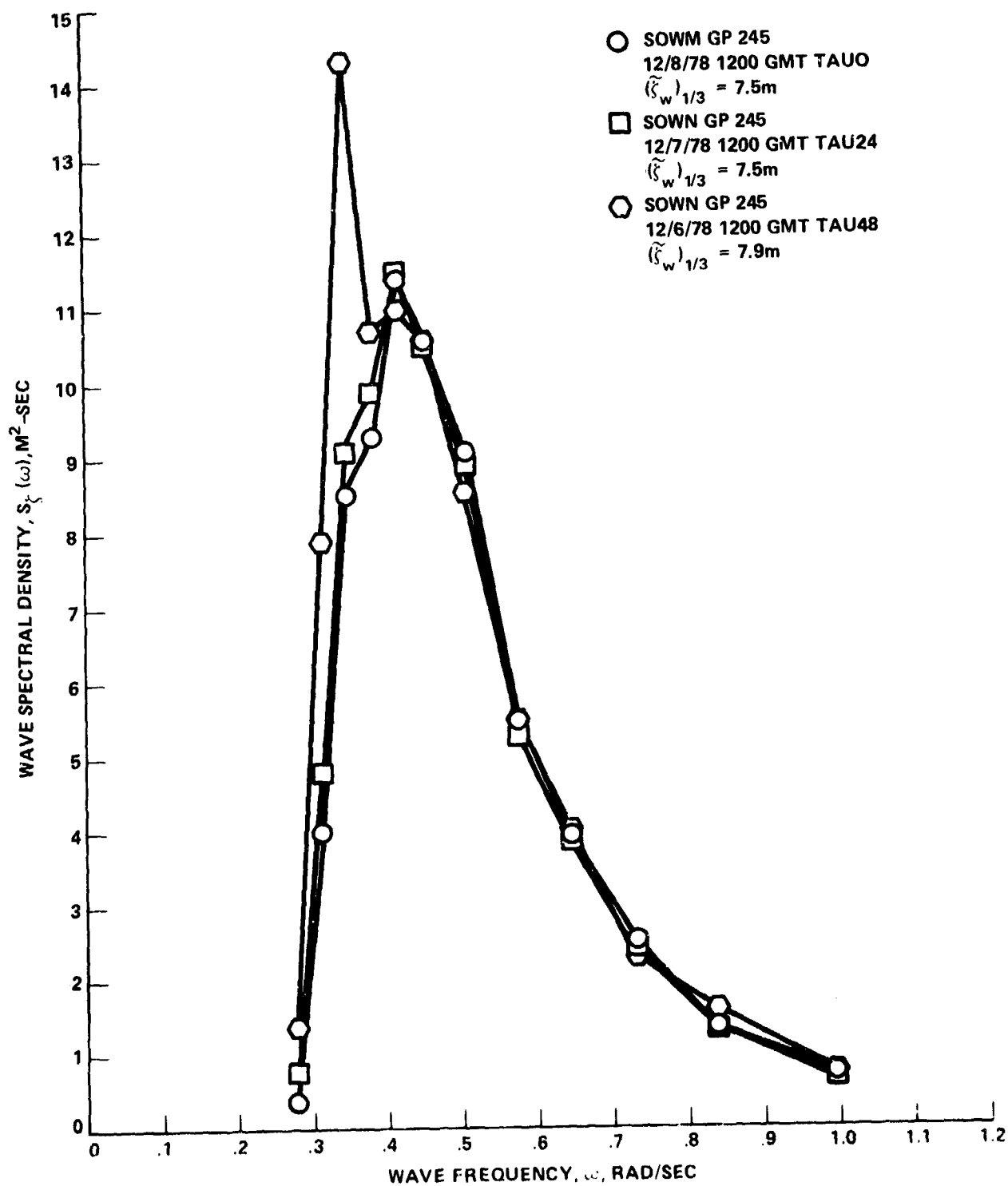


Figure 15 - Comparison of SOWM Forecasts Projected to Same Day -
TYDEMAN Trials, 8 December 1978

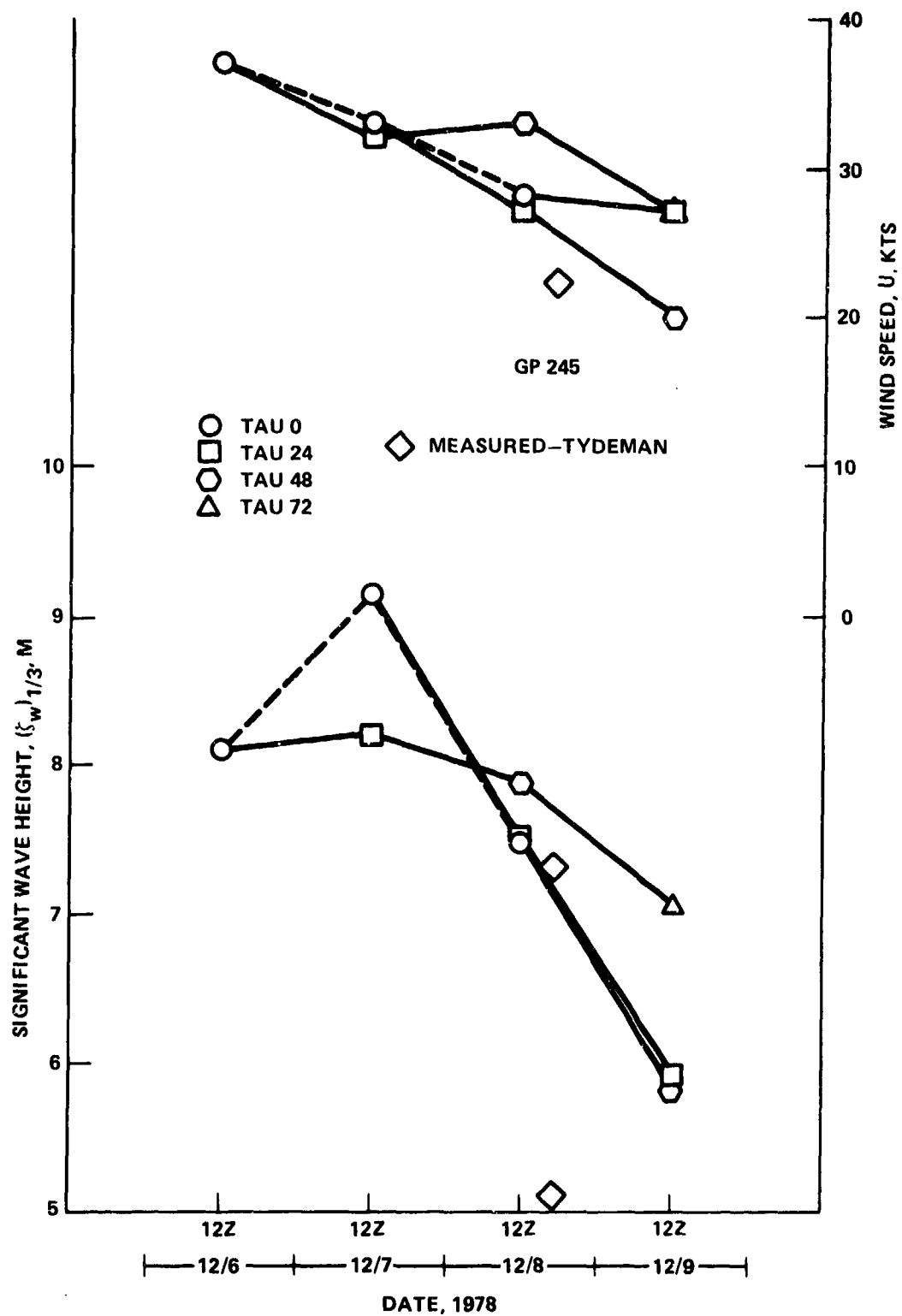


Figure 16 - Comparison of TYDEMAN Measurements and SOWM Forecasts for Wind Speed and Significant Wave Height, GP 245

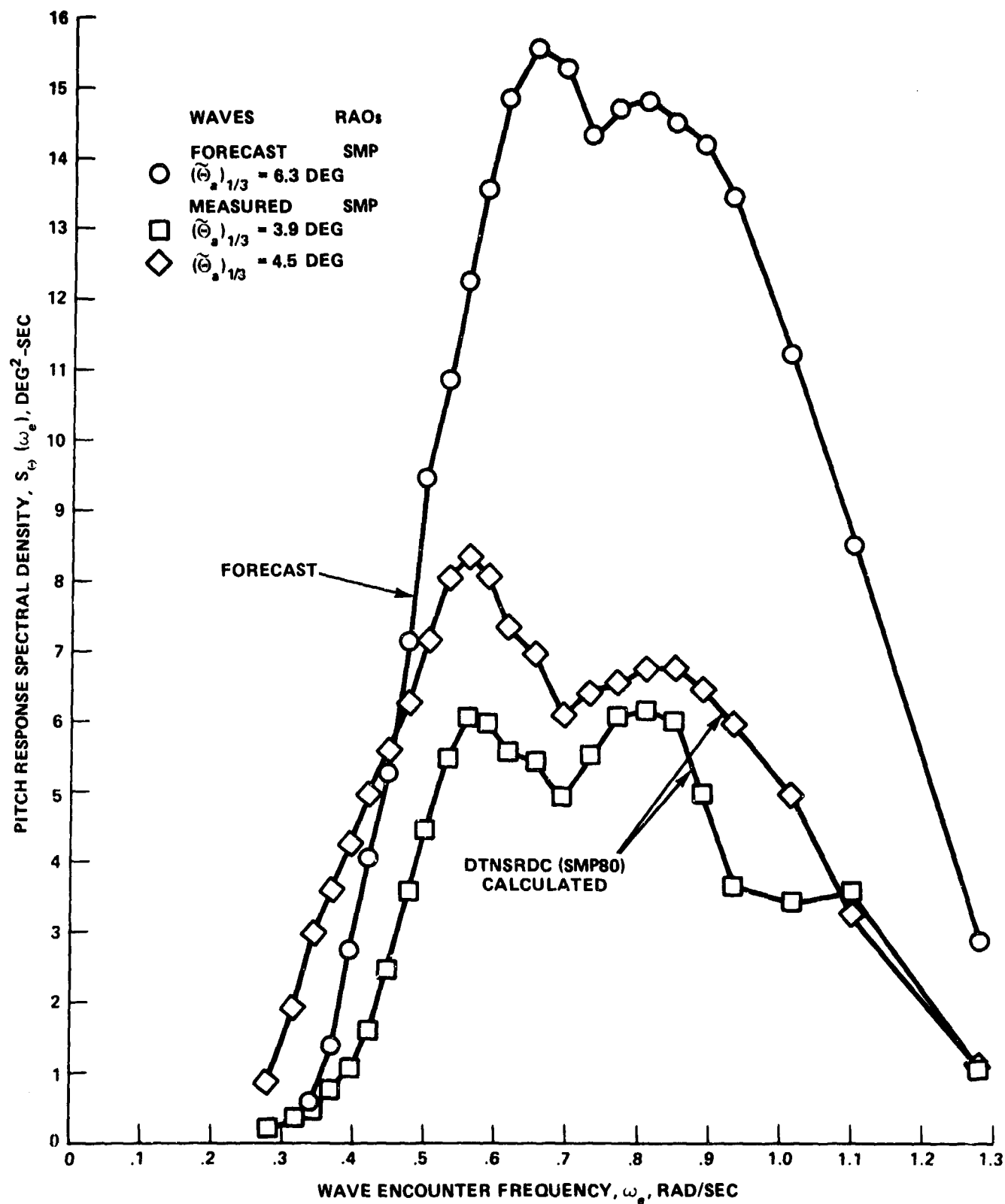


Figure 17 - TYDEMAN Pitch Response in Head Seas, 8 December 1978

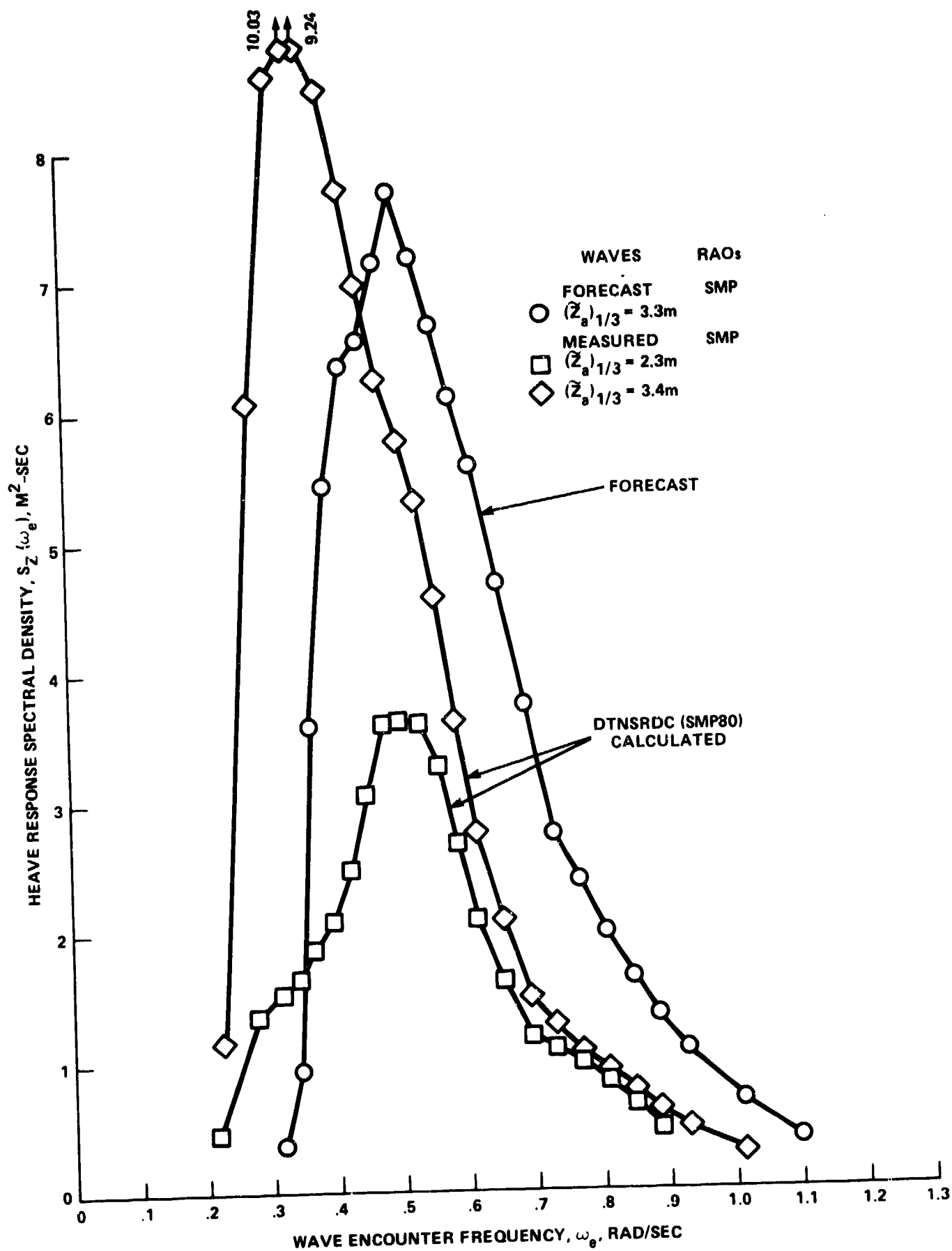


Figure 18 - TYDEMAN Heave Response in Head Seas, 8 December 1978

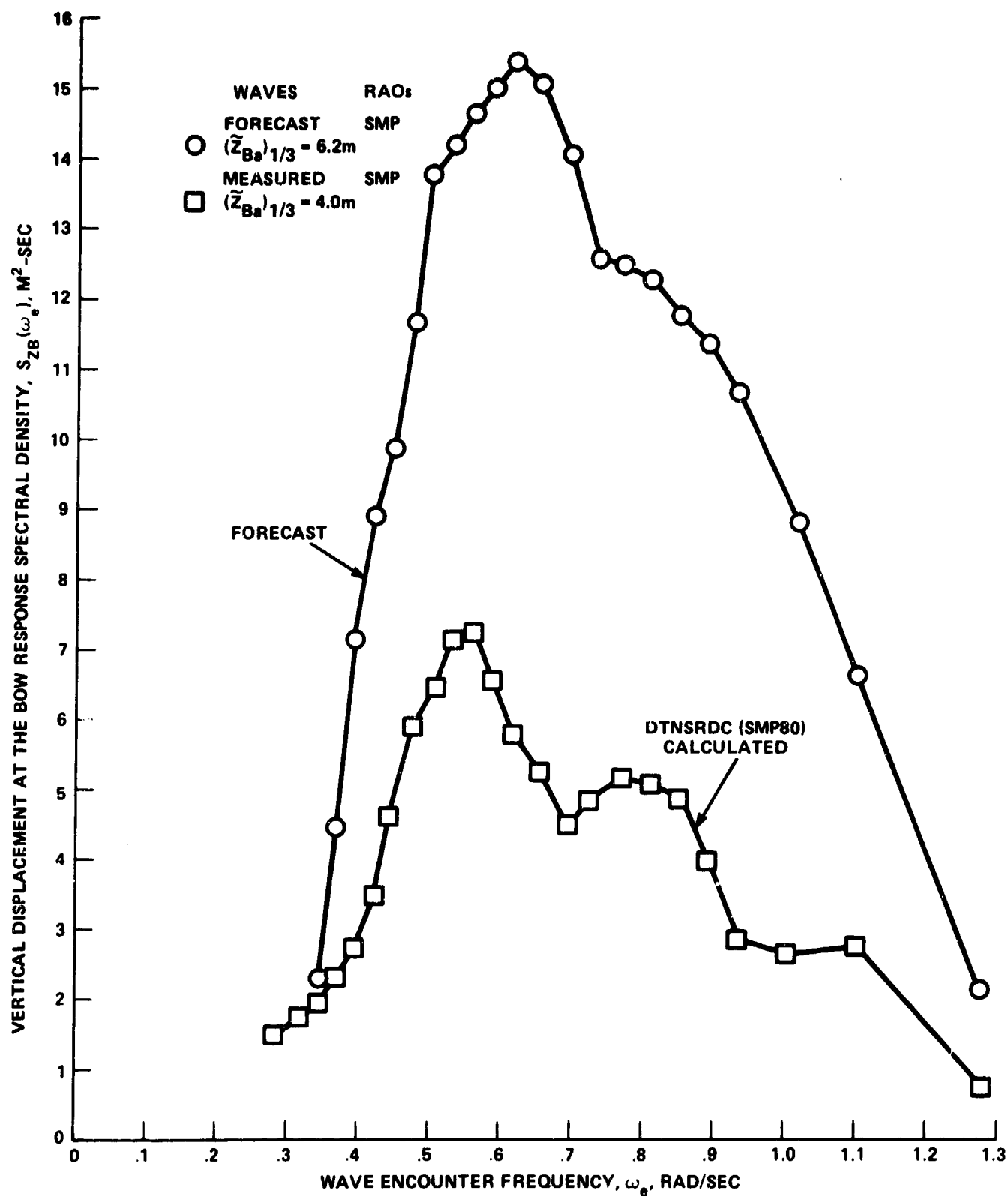


Figure 19 - TYDEMAN Vertical Displacement at the Bow Response in Head Seas, 8 December 1978

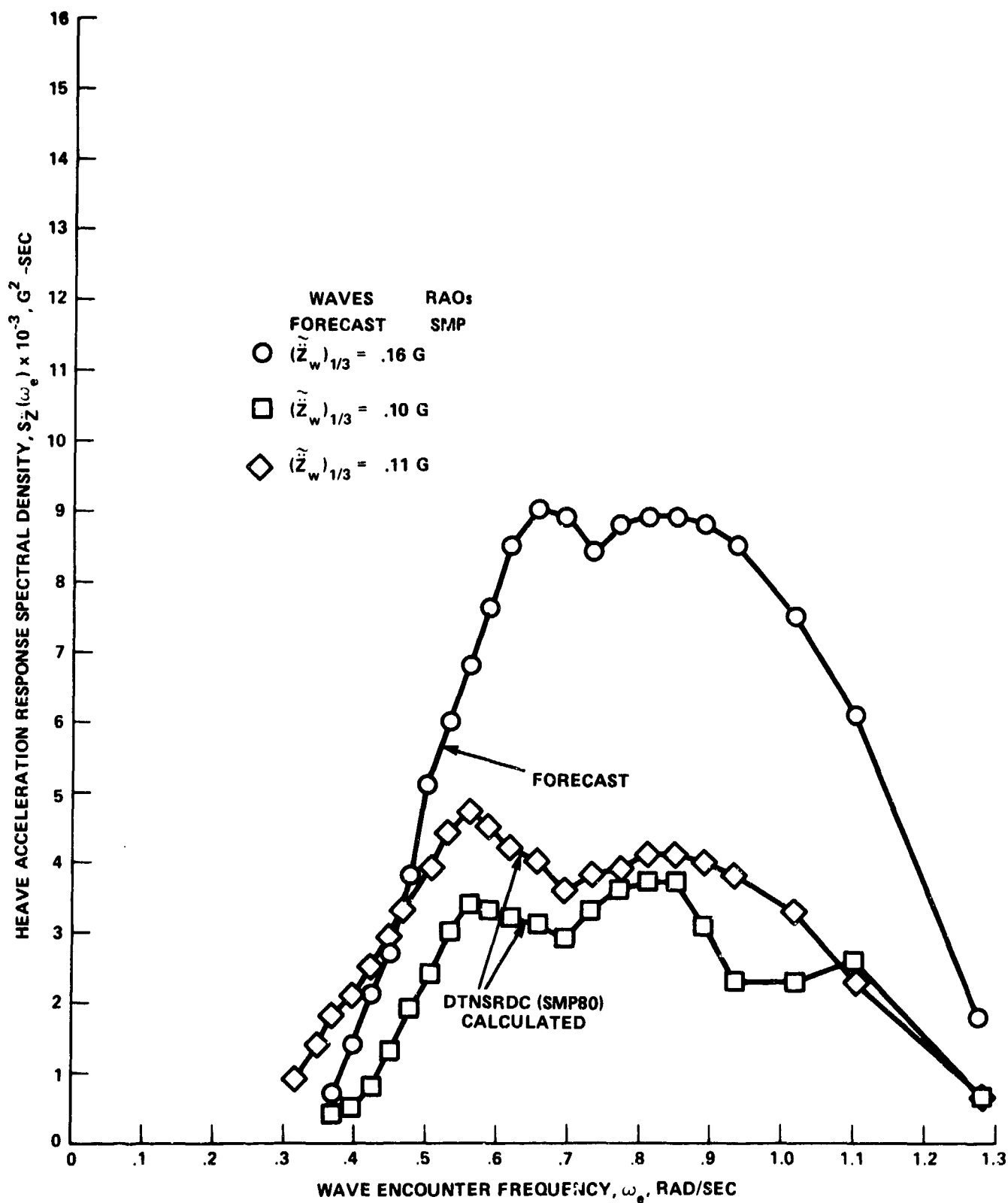


Figure 20 - TYDEMAN Heave Acceleration Response in Head Seas, 8 December 1978

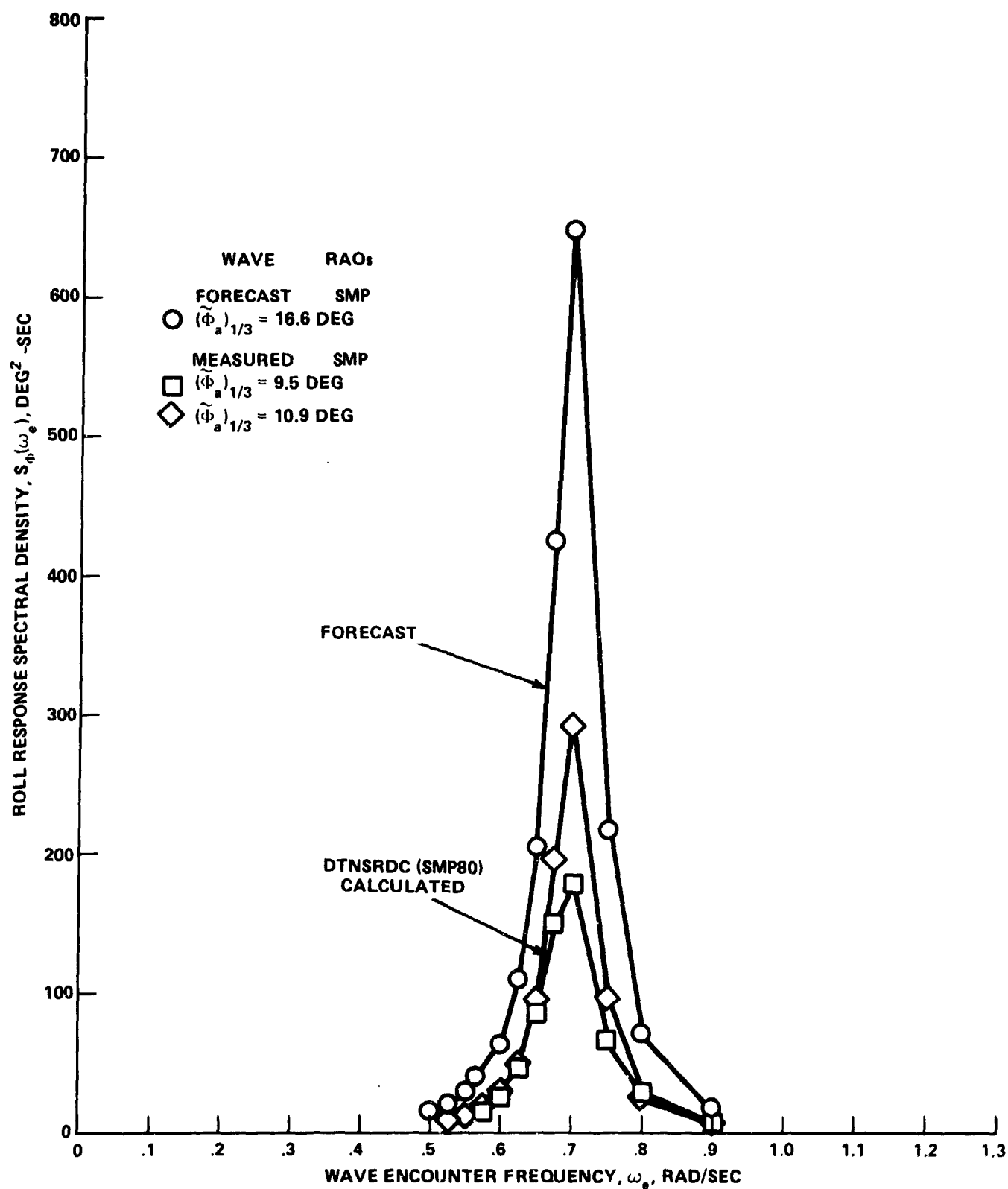


Figure 21 - TYDEMAN Roll Response in Beam Seas, 8 December 1978

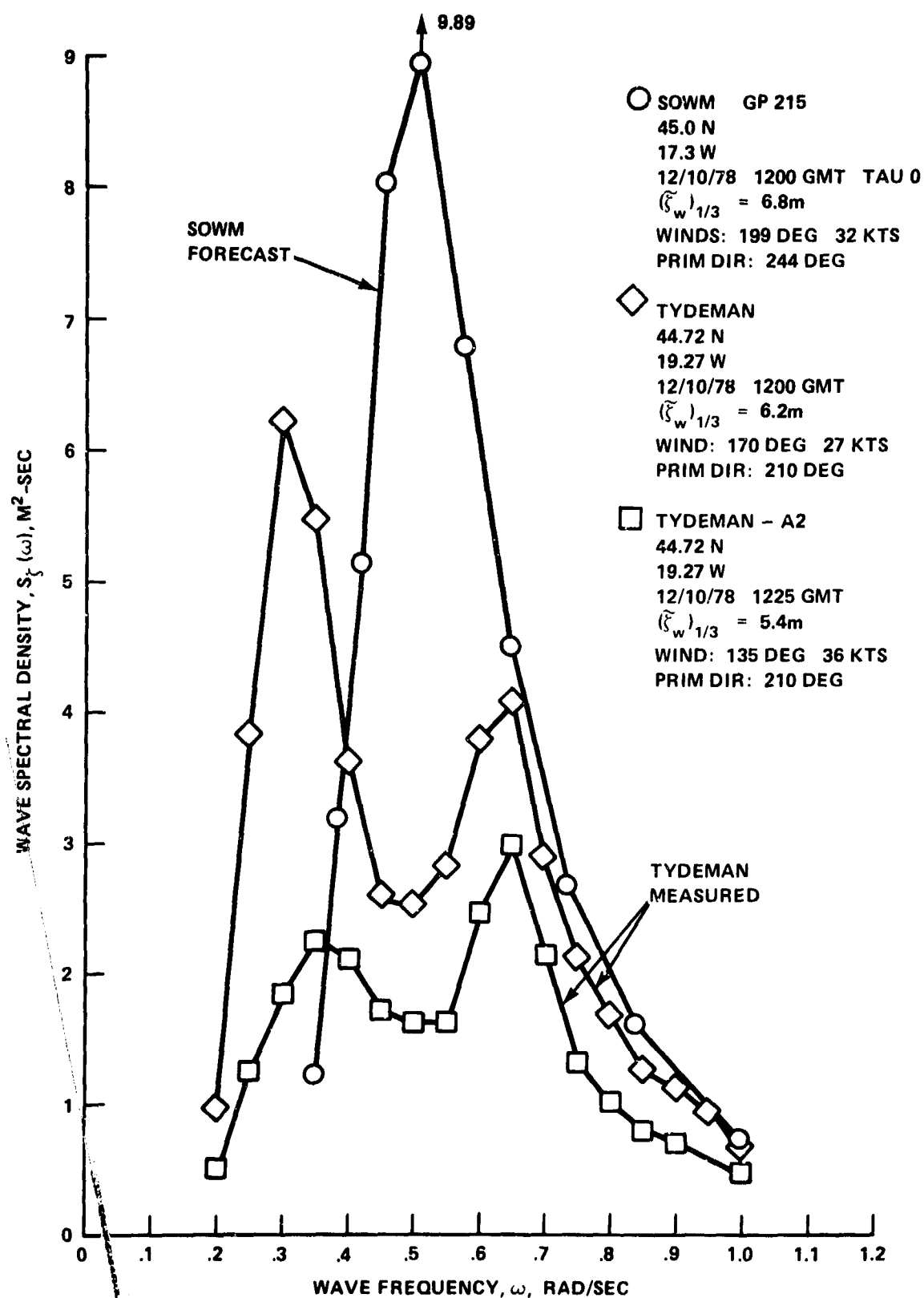


Figure 22 - Comparison Wave Spectral Density, Measured and Forecast - TYDEMAN Trials, 10 December 1978

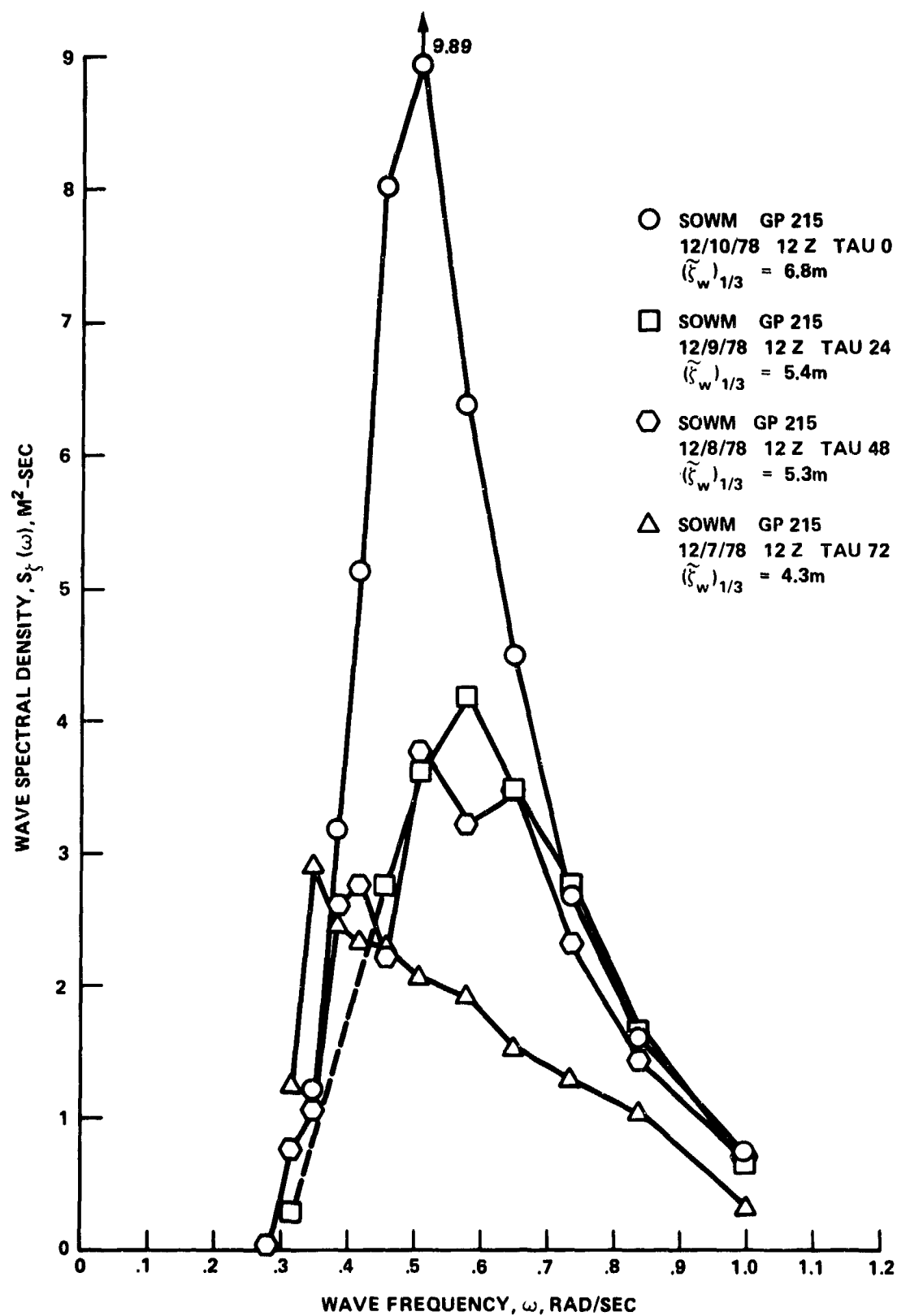


Figure 23 - Comparison of SOWM Forecasts Projected to the Same Day - TYDEMAN Trials, 10 December 1978

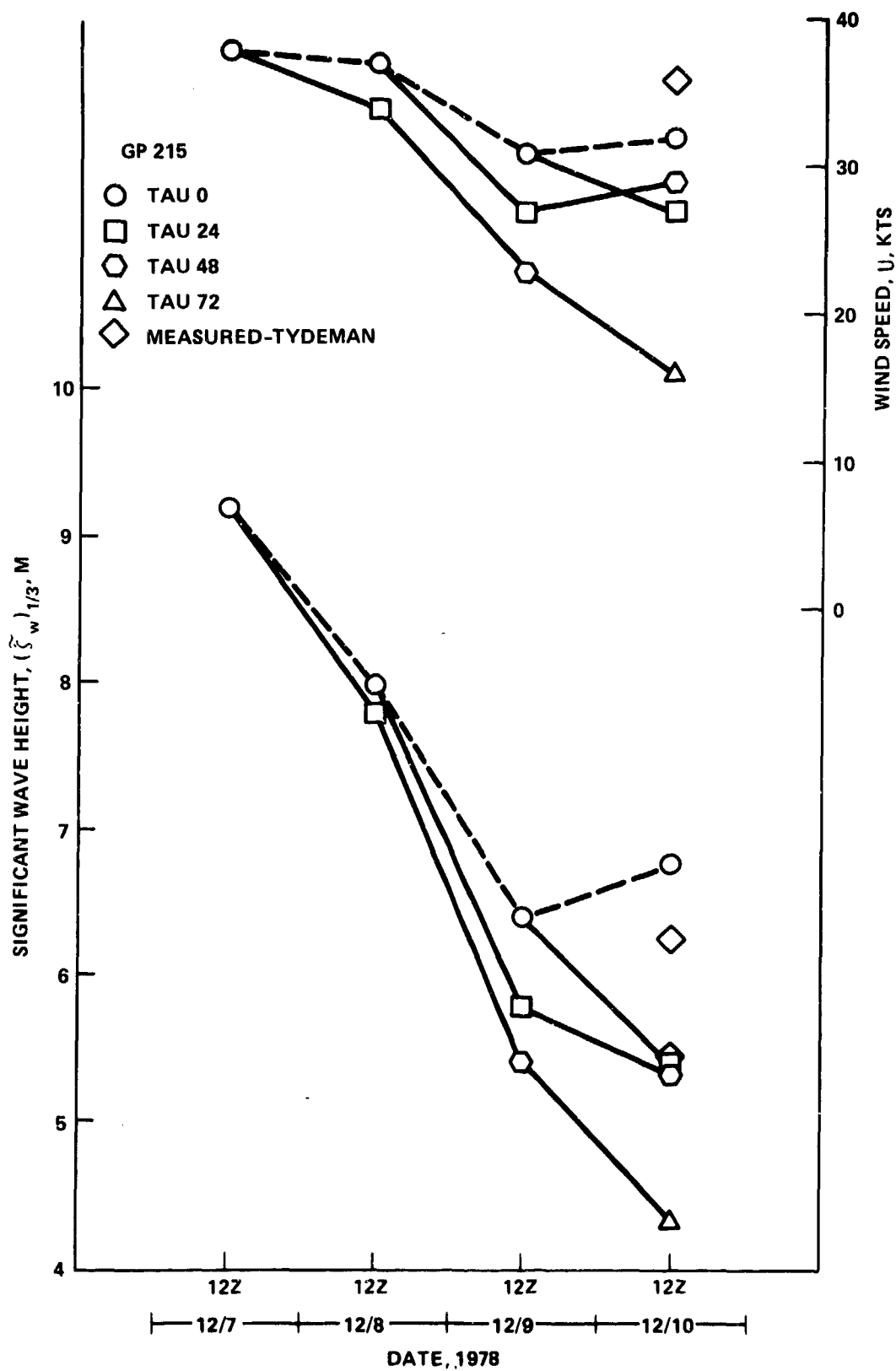


Figure 24 - Comparison of TYDEMAN Measurements and SOWM Forecasts for Wind Speed and Significant Wave Height, GP 215

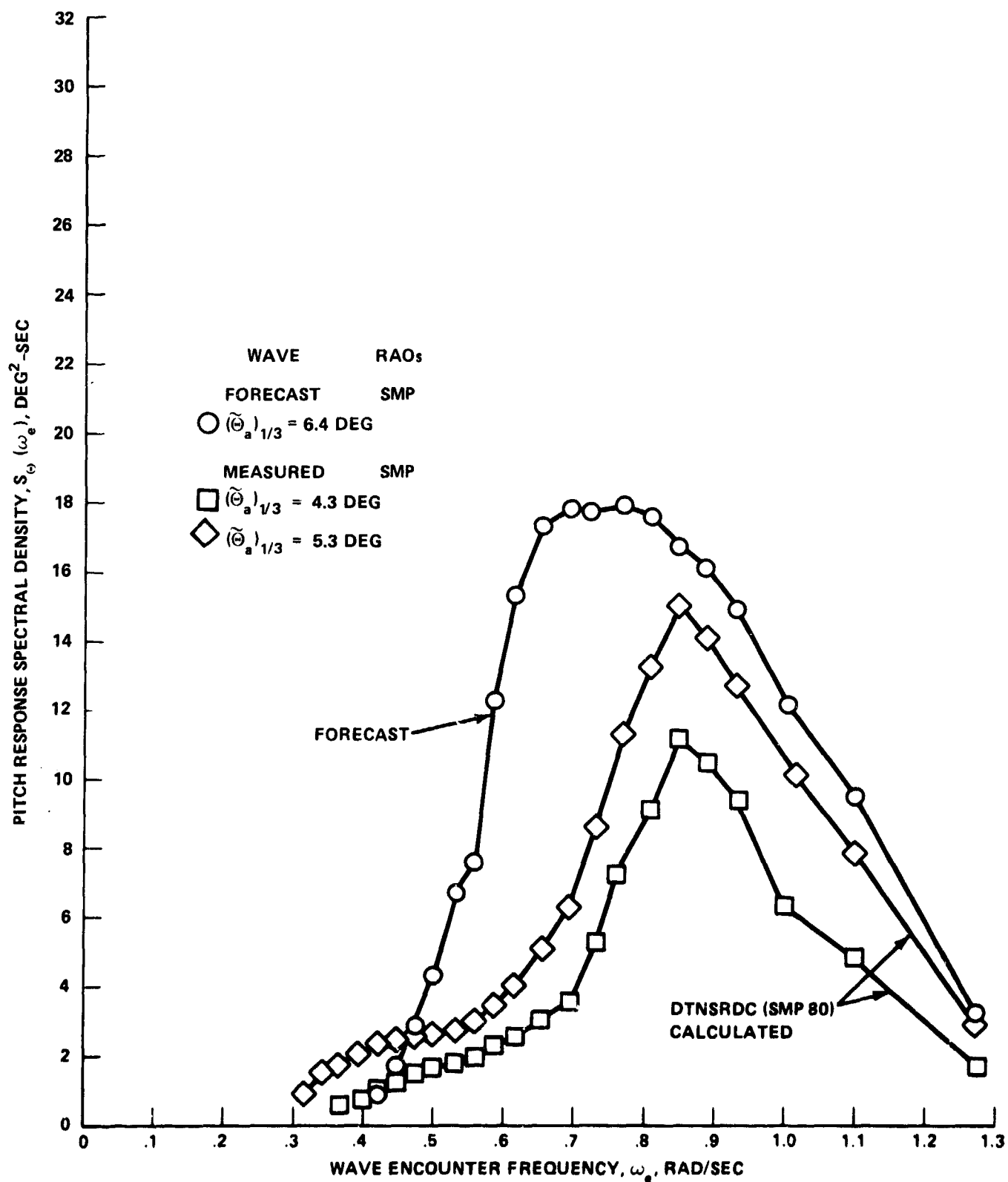


Figure 25 - TYDEMAN Pitch Response In Head Seas, 10 December 1978

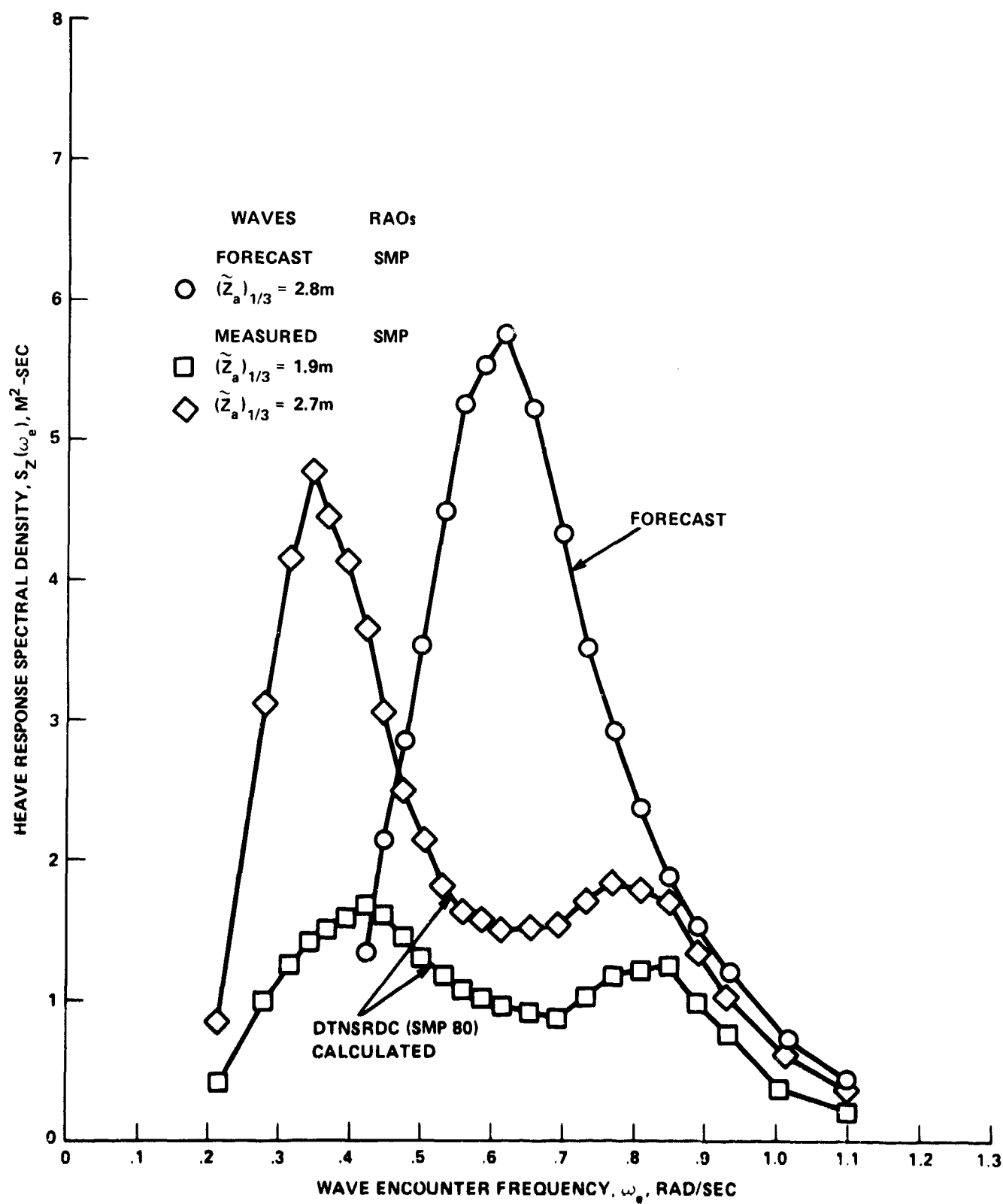


Figure 26 - TYDEMAN Heave Response in Head Seas, 10 December 1978

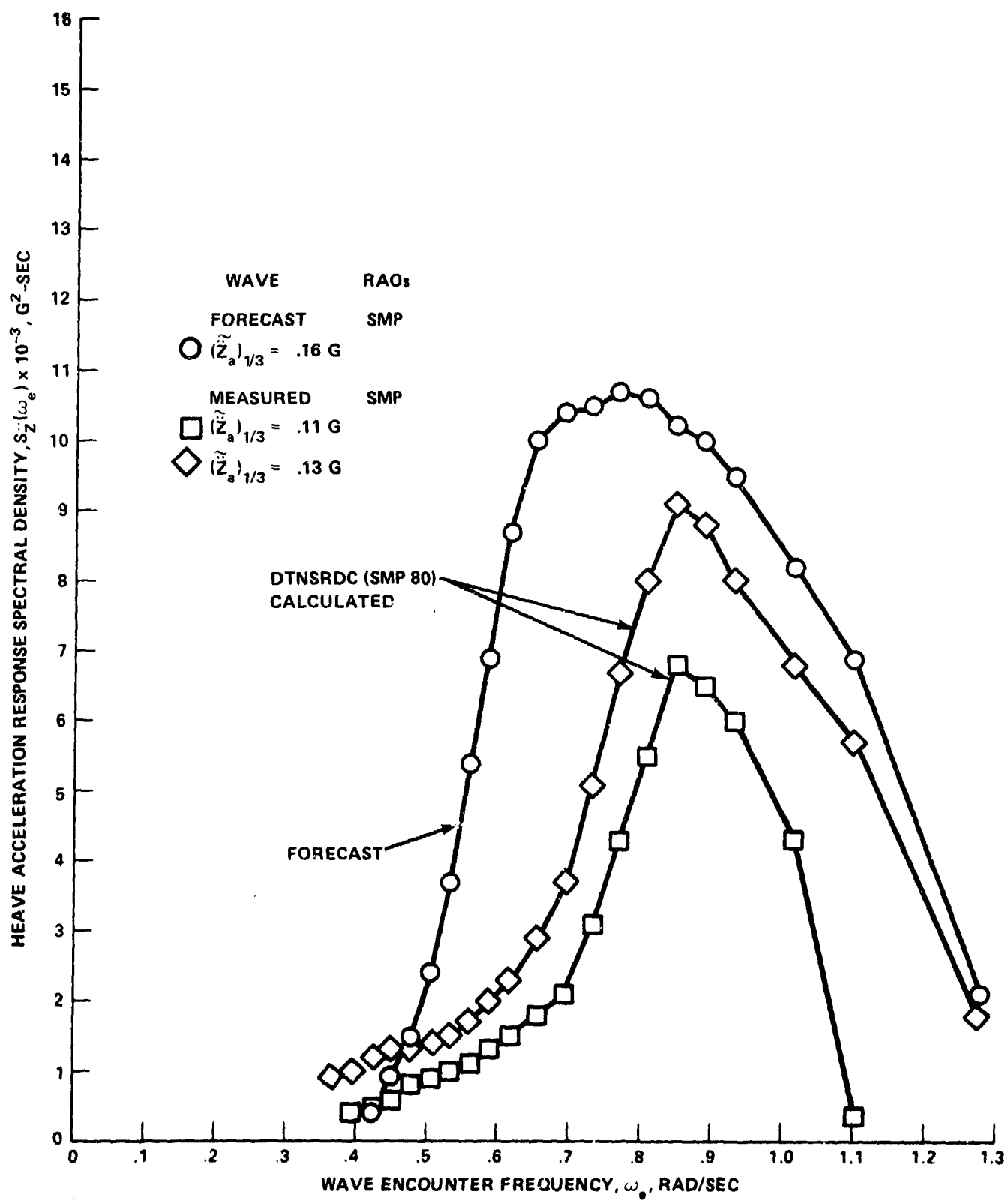


Figure 27 - TYDEMAN Heave Acceleration Response in Head Seas, 10 December 1978

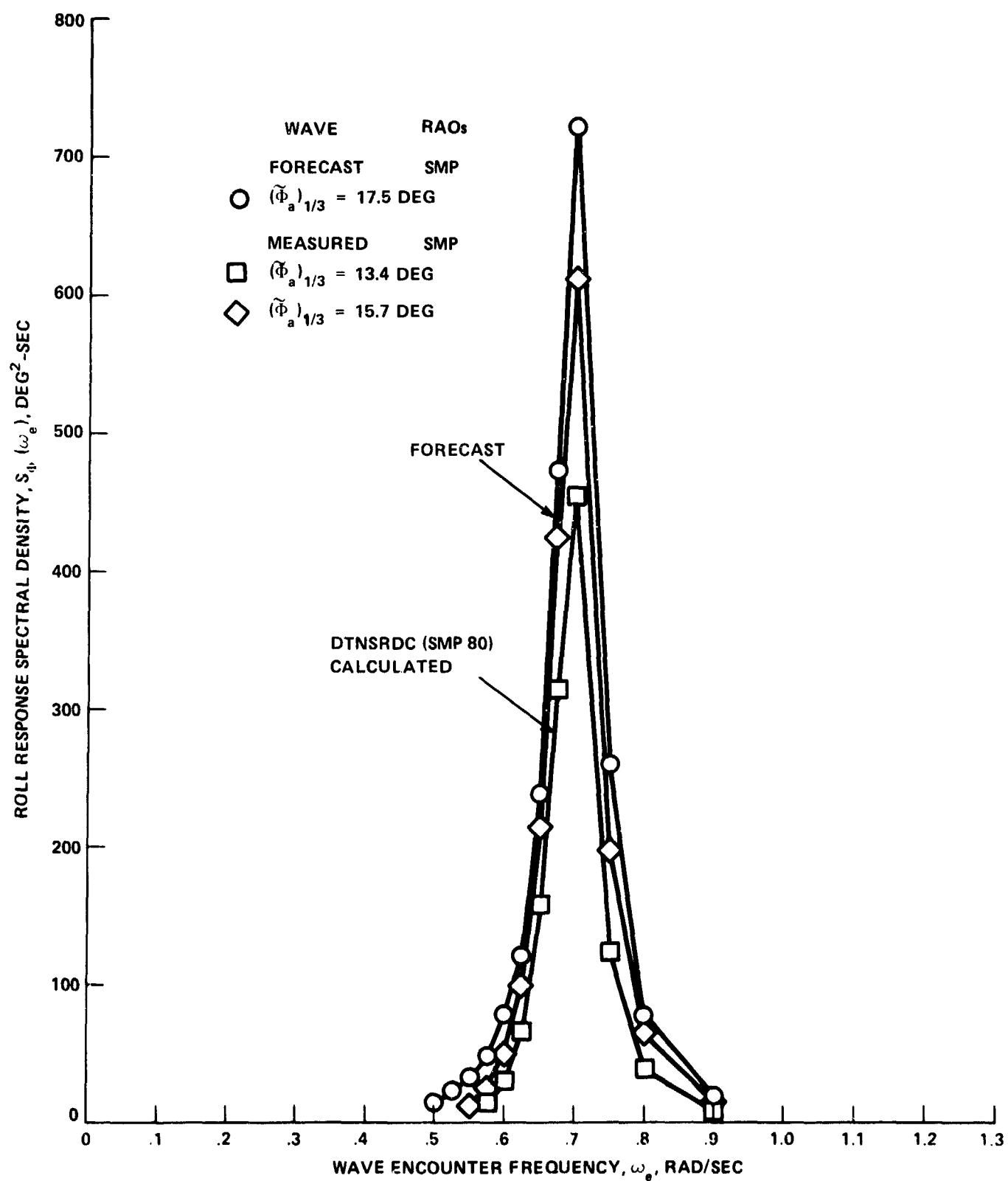


Figure 28 - TYDEMAN Roll Response in Beam Seas, 10 December 1978

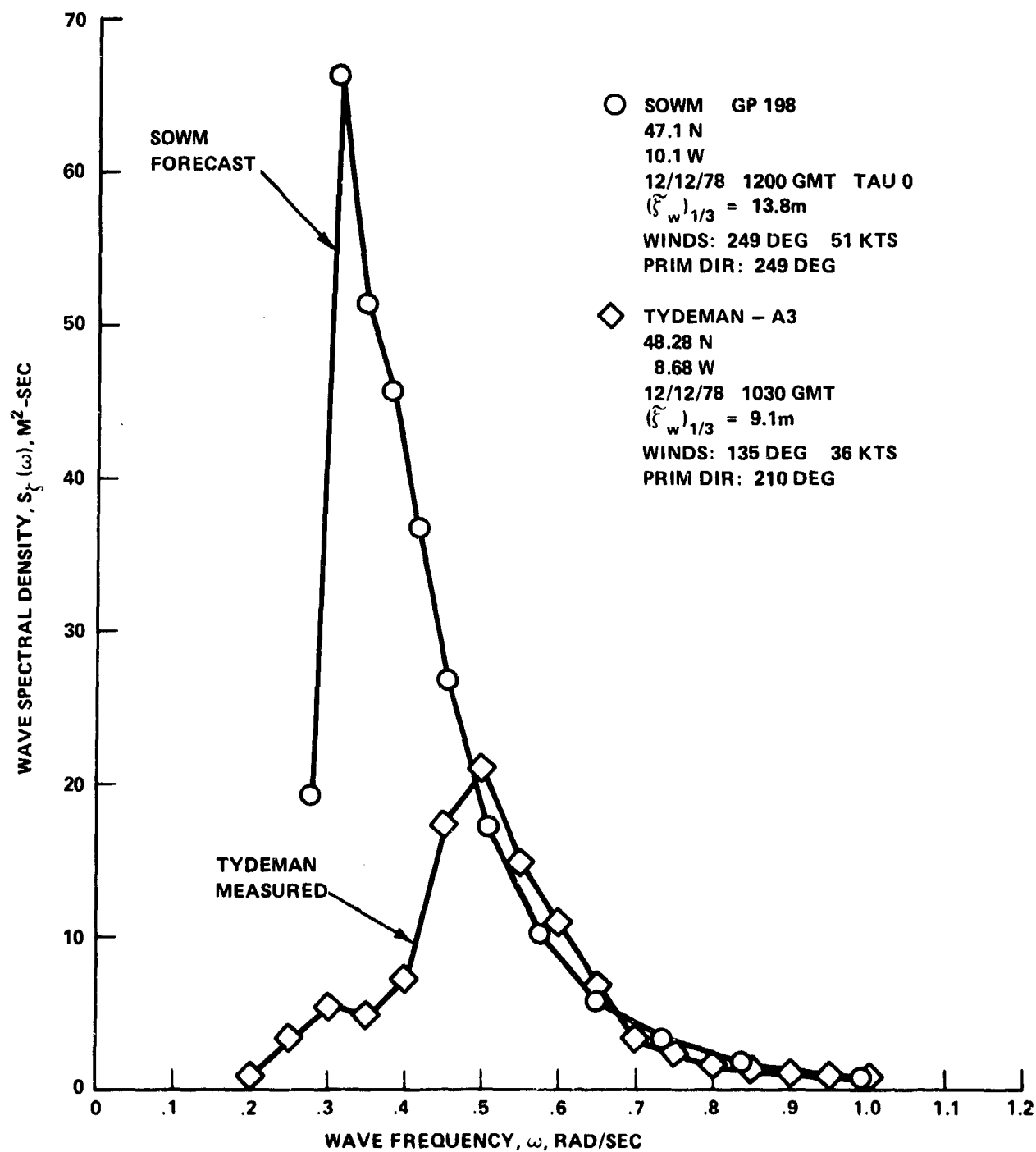


Figure 29 - Comparison Wave Spectral Density, Measured and Forecast - TYDEMAN Trials, 12 December 1978

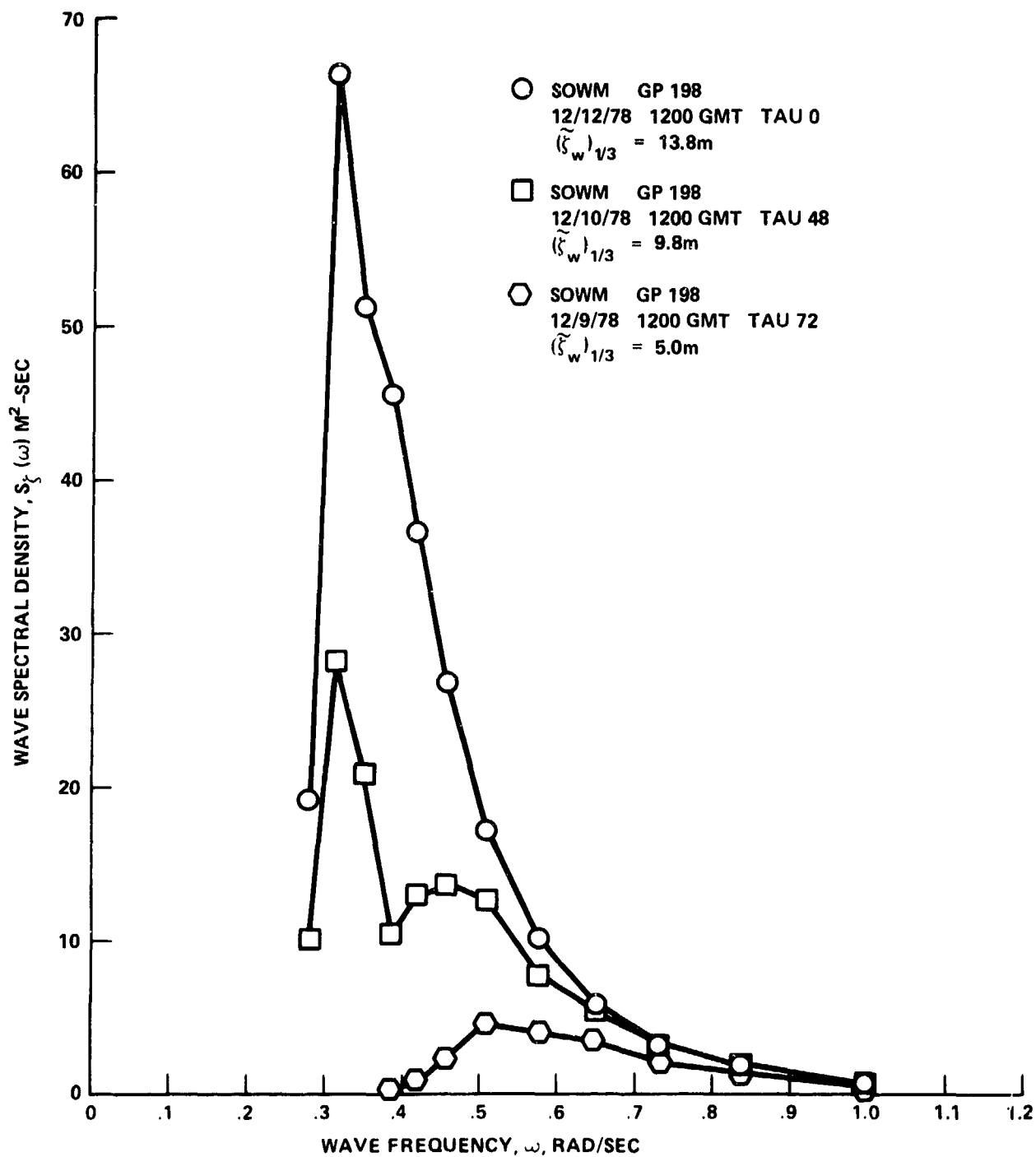


Figure 30 - Comparison of SOWM Forecasts Projected to Same Day -
TYDEMAN Trials, 12 December 1978

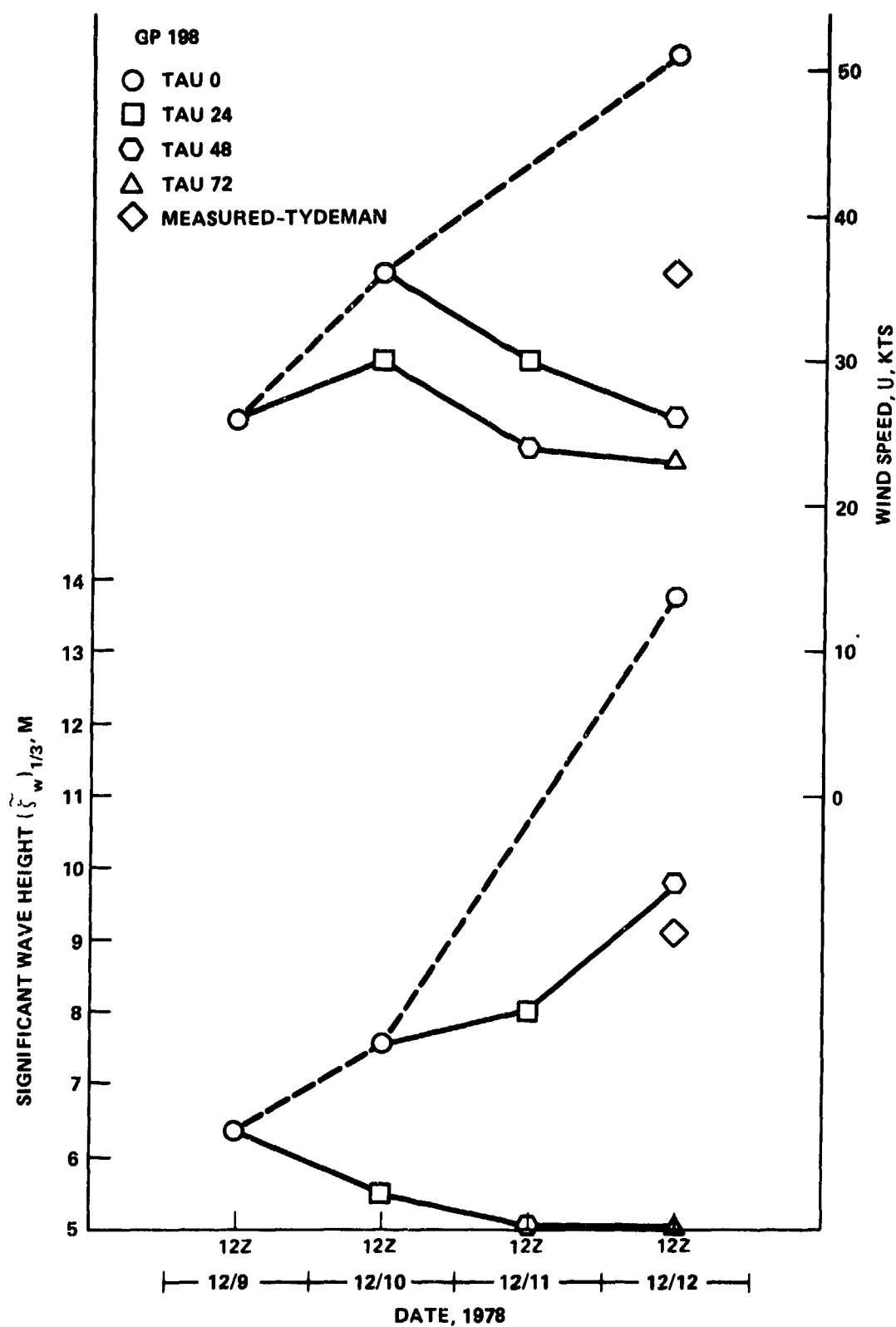


Figure 31 - Comparison of TYDEMAN Measurements and SOWM Forecasts for Wind Speed and Significant Wave Height, GP 198

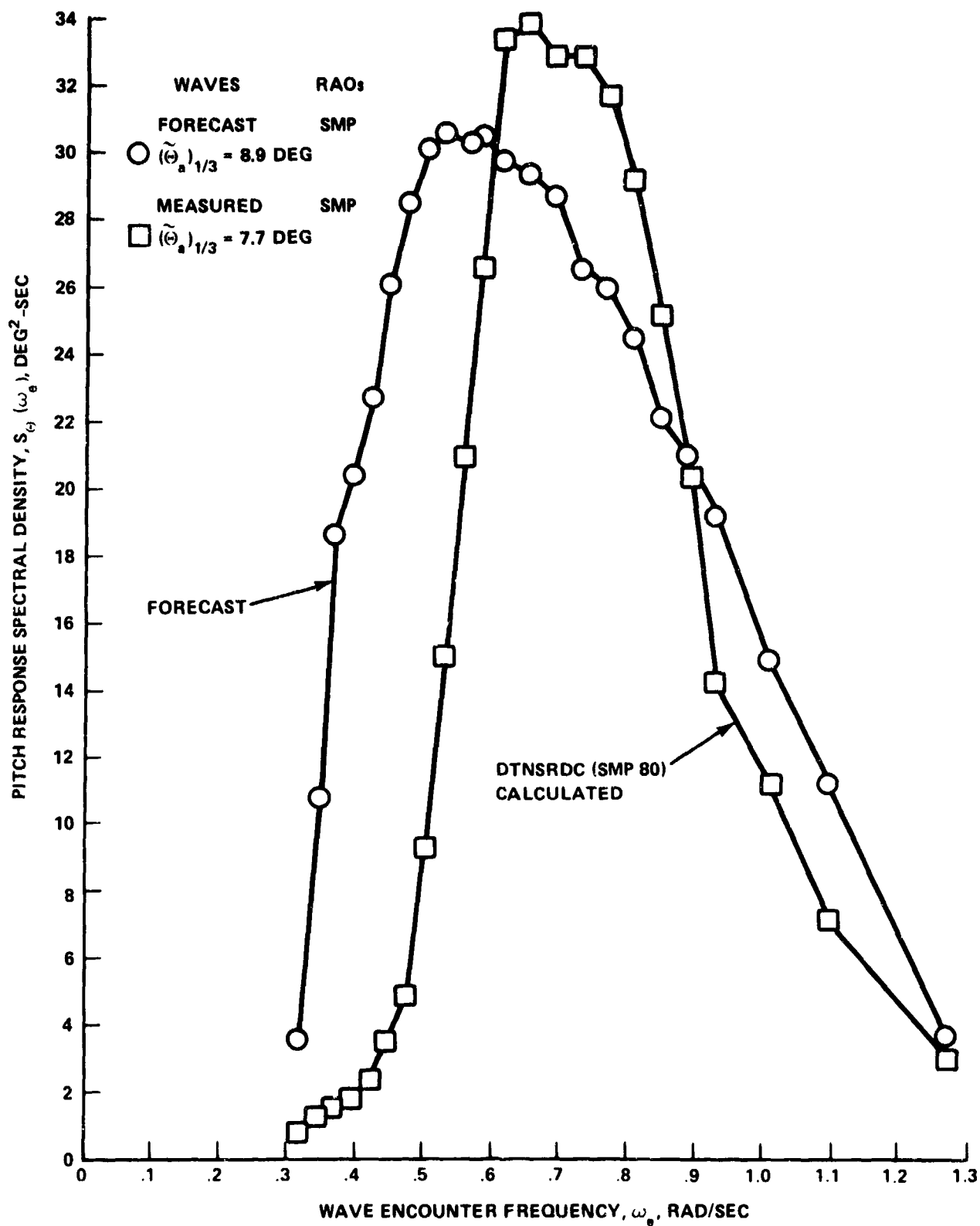


Figure 32 - TYDEMAN Pitch Response in Head Seas, 12 December 1978

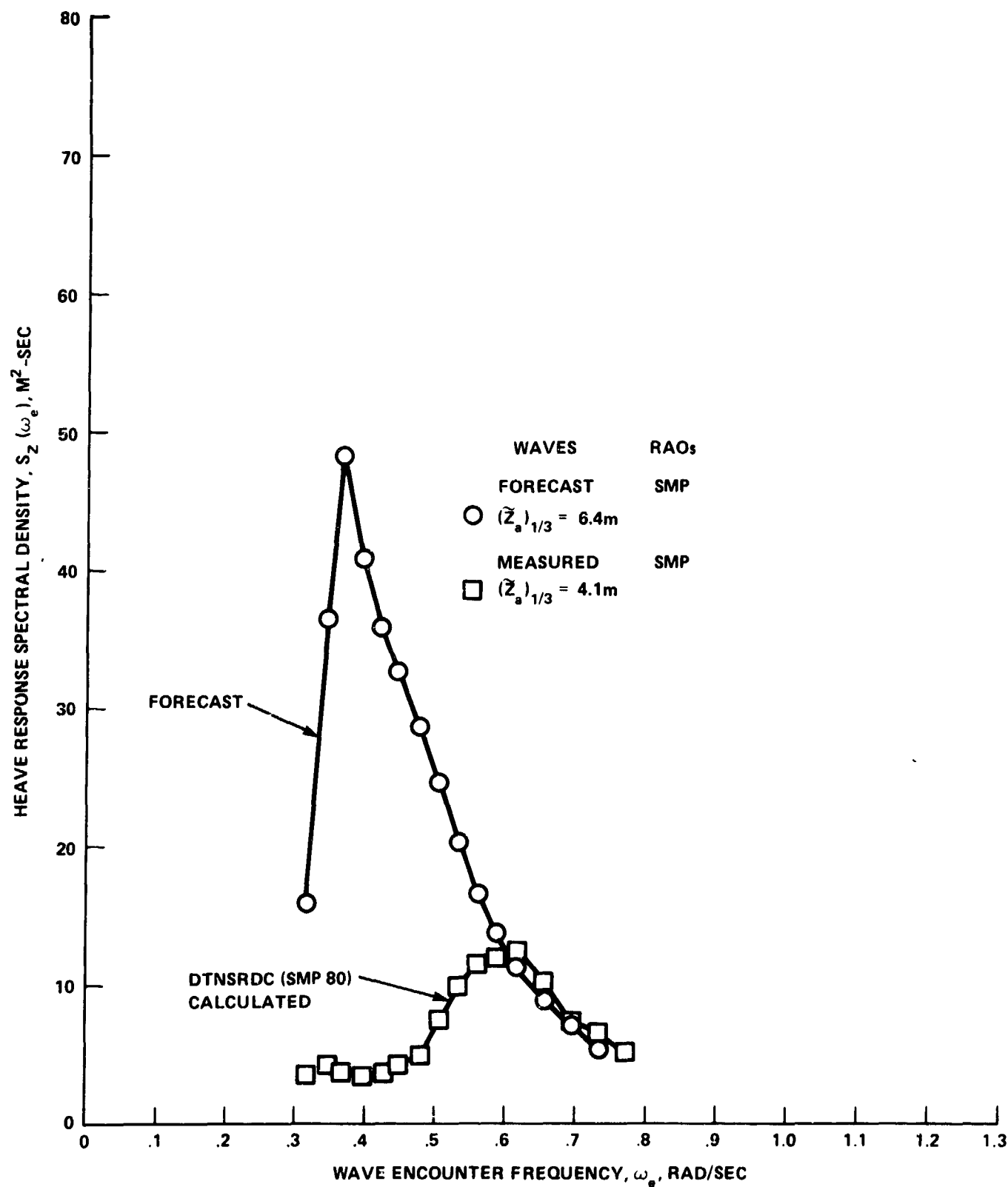


Figure 33 - TYDEMAN Heave Response in Head Seas, 12 December 1978

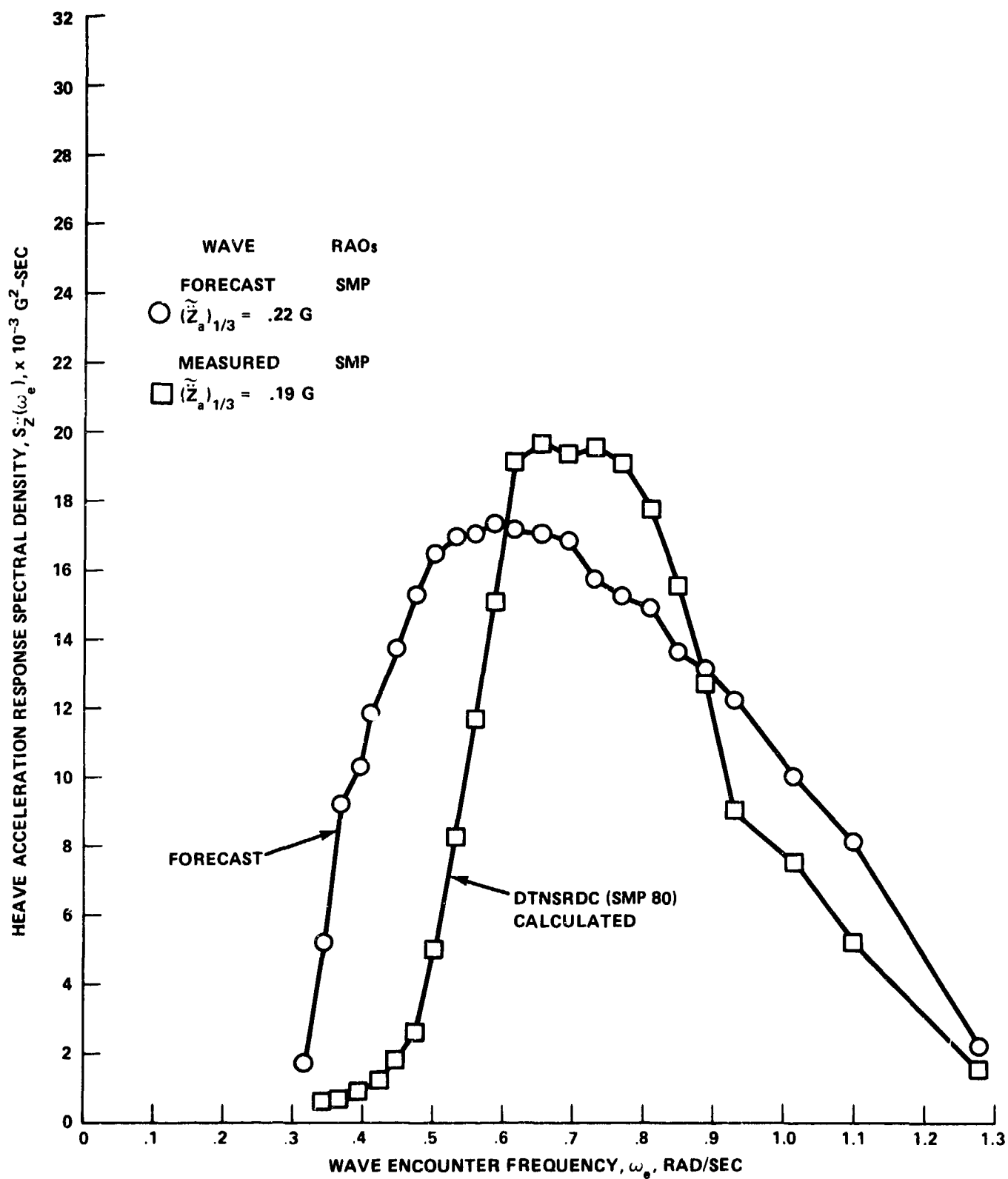


Figure 34 - TYDEMAN Heave Acceleration Response in Head Seas, 12 December 1978

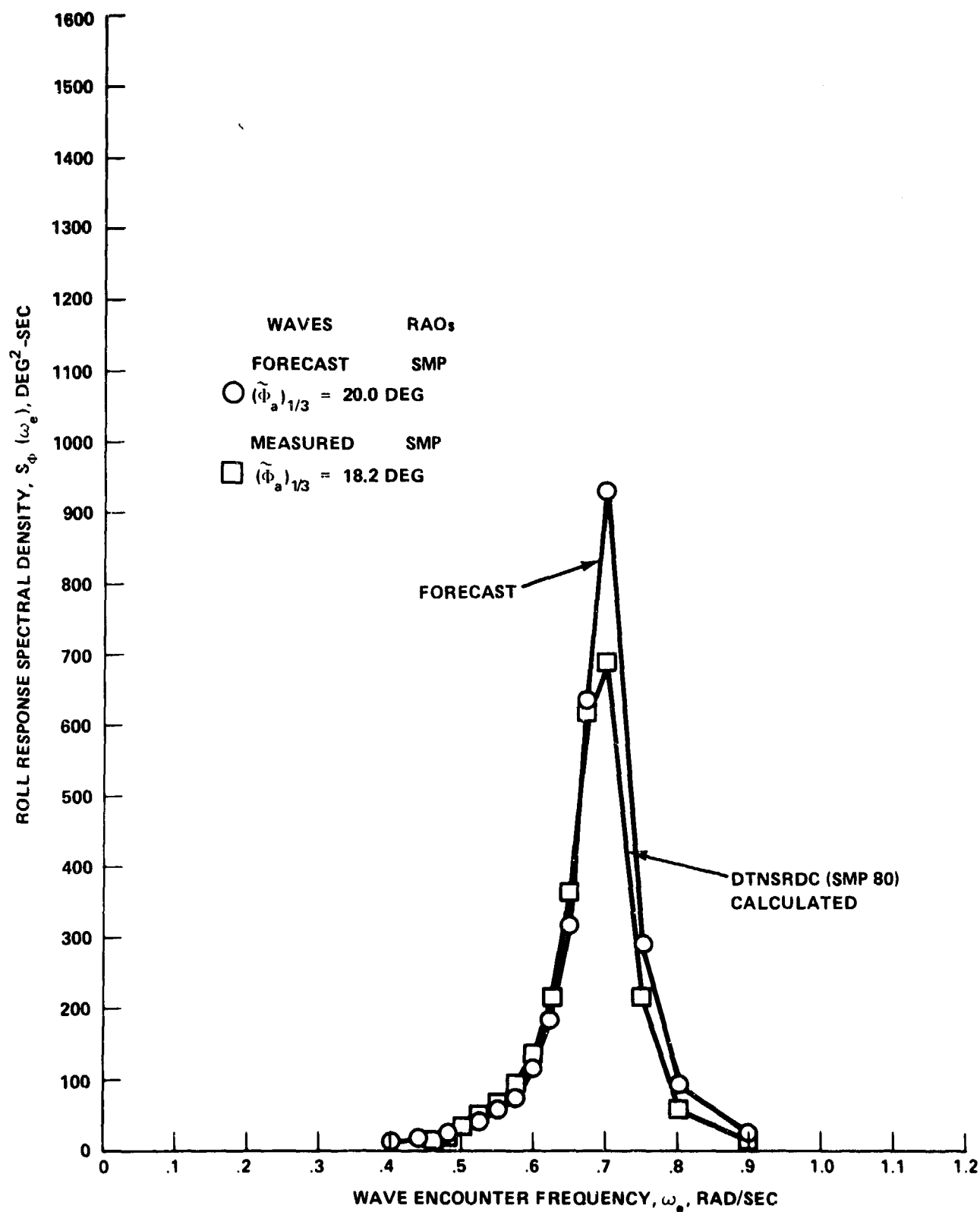


Figure 35 - TYDEMAN Roll Response in Beam Seas, 12 December 1978

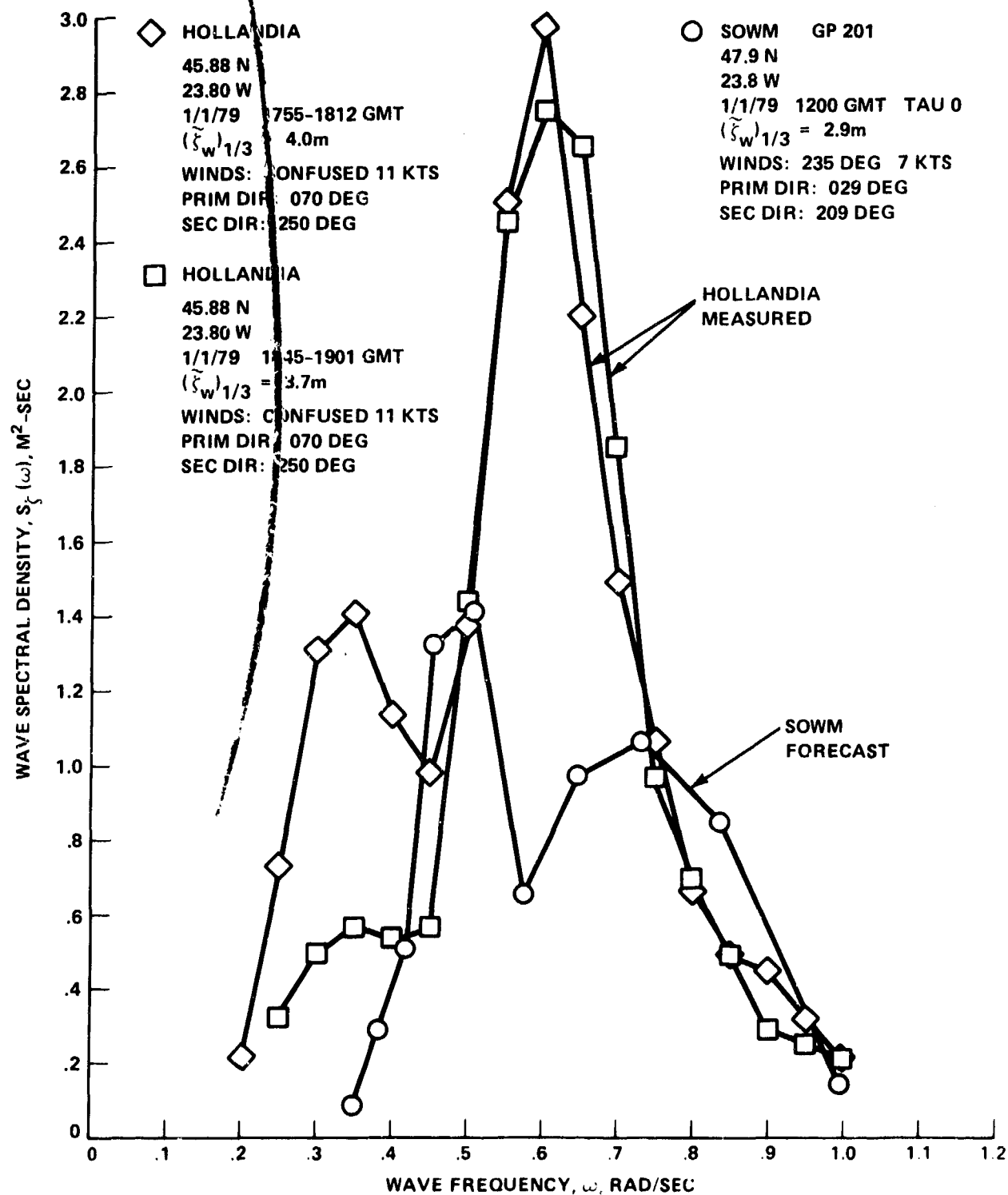


Figure 36 - Comparison Wave Spectral Density, Measured and Forecast -
 HOLLANDIA Trials, 1 January 1979

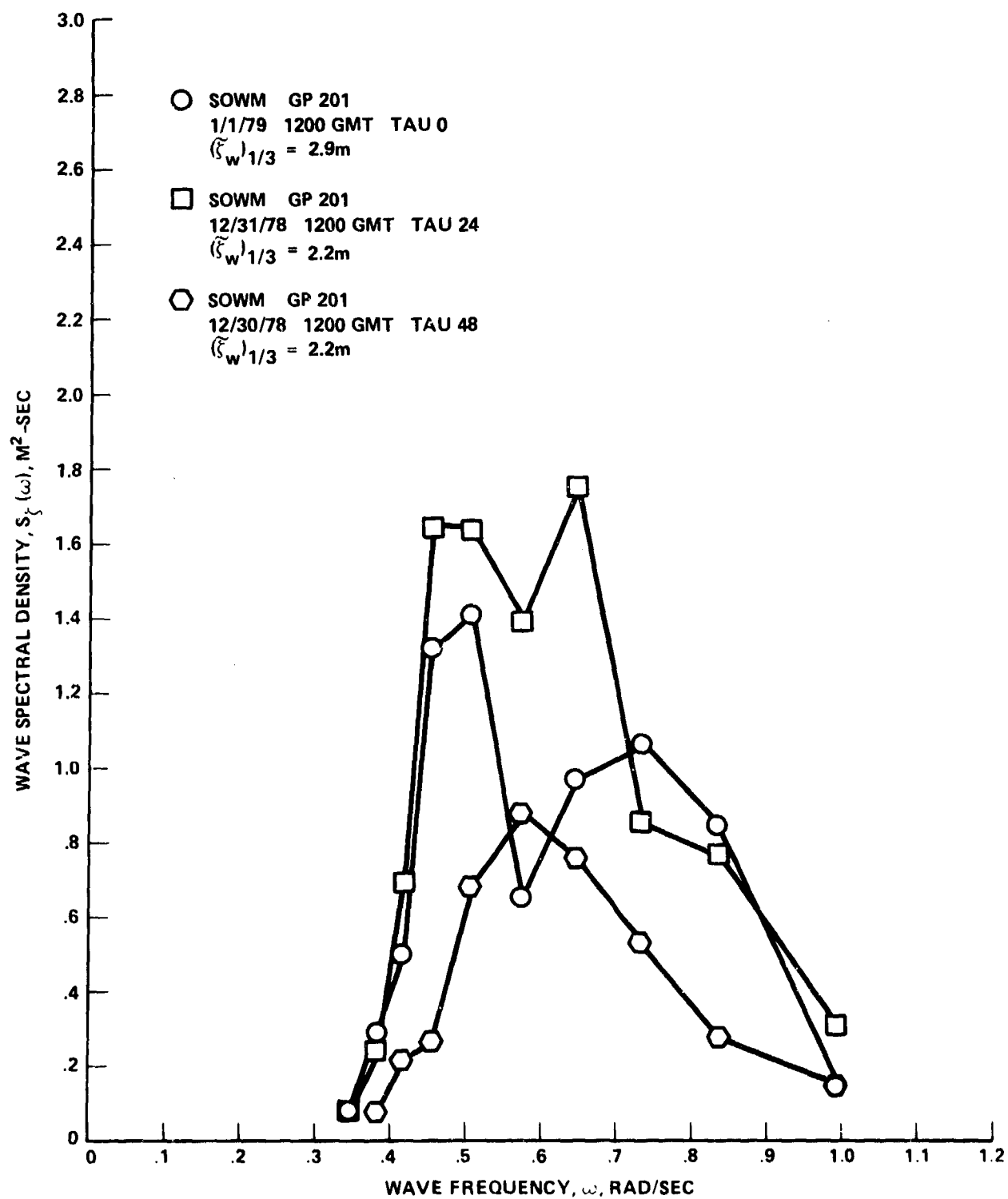


Figure 37 - Comparison of SOWM Forecasts Projected to the Same Day - HOLLANDIA Trials, 1 January 1979

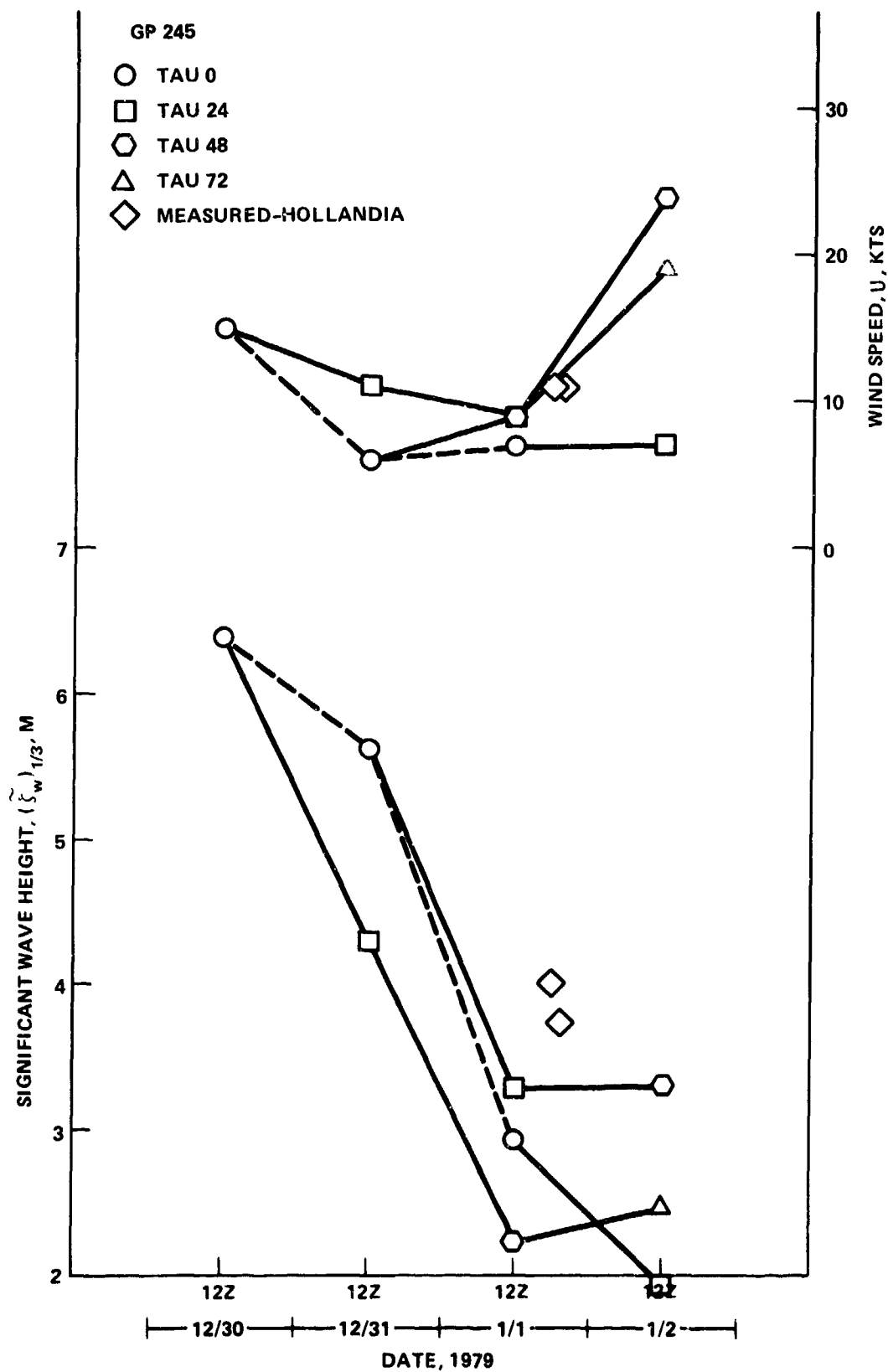


Figure 38 - Comparison of HOLLANDIA Measurements and SOWM Forecasts for Wind Speed and Significant Wave Height, GP 245

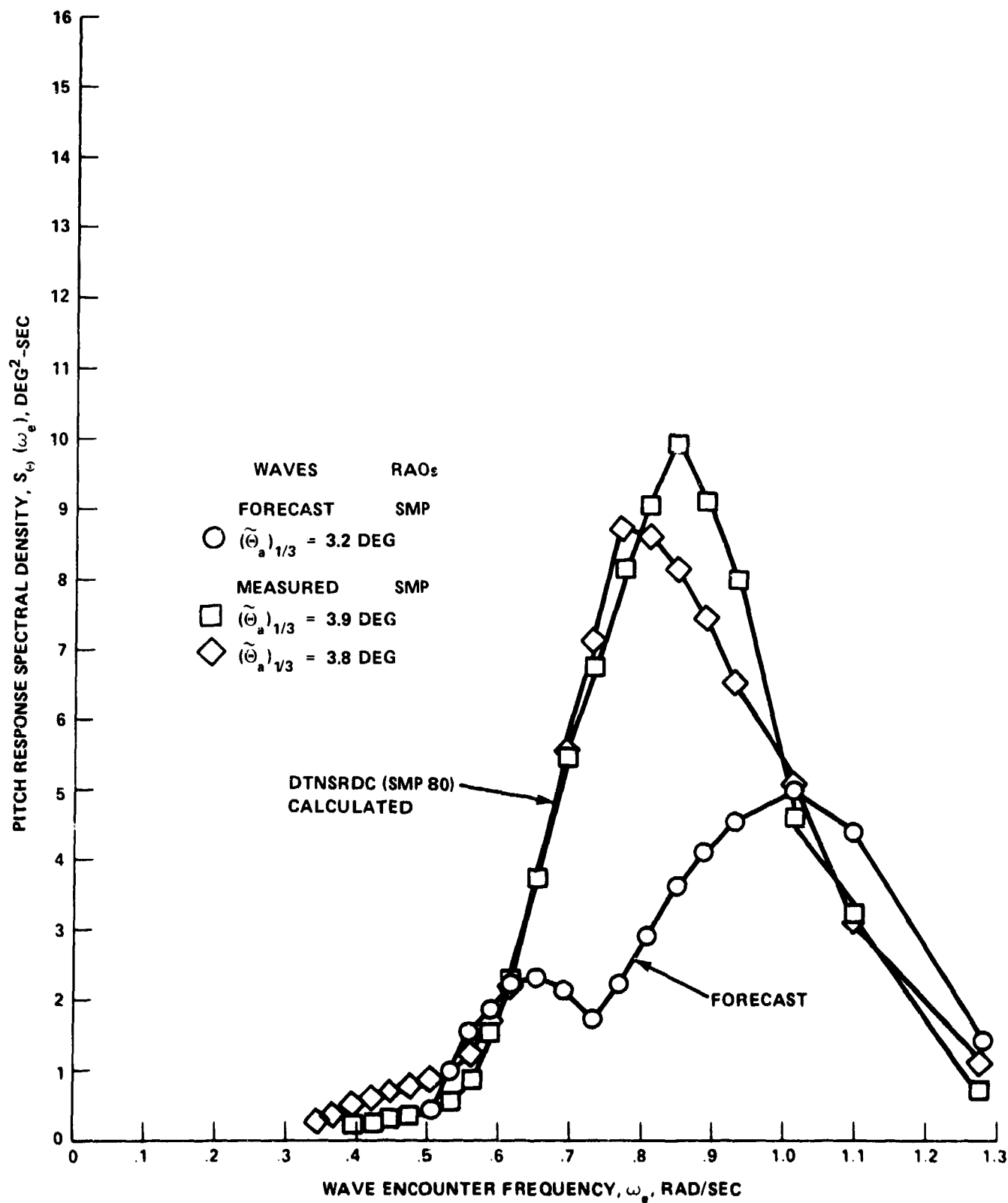


Figure 39 - TYDEMAN Pitch Response in Head Seas with HOLLANDIA Spectra, 1 January 1979

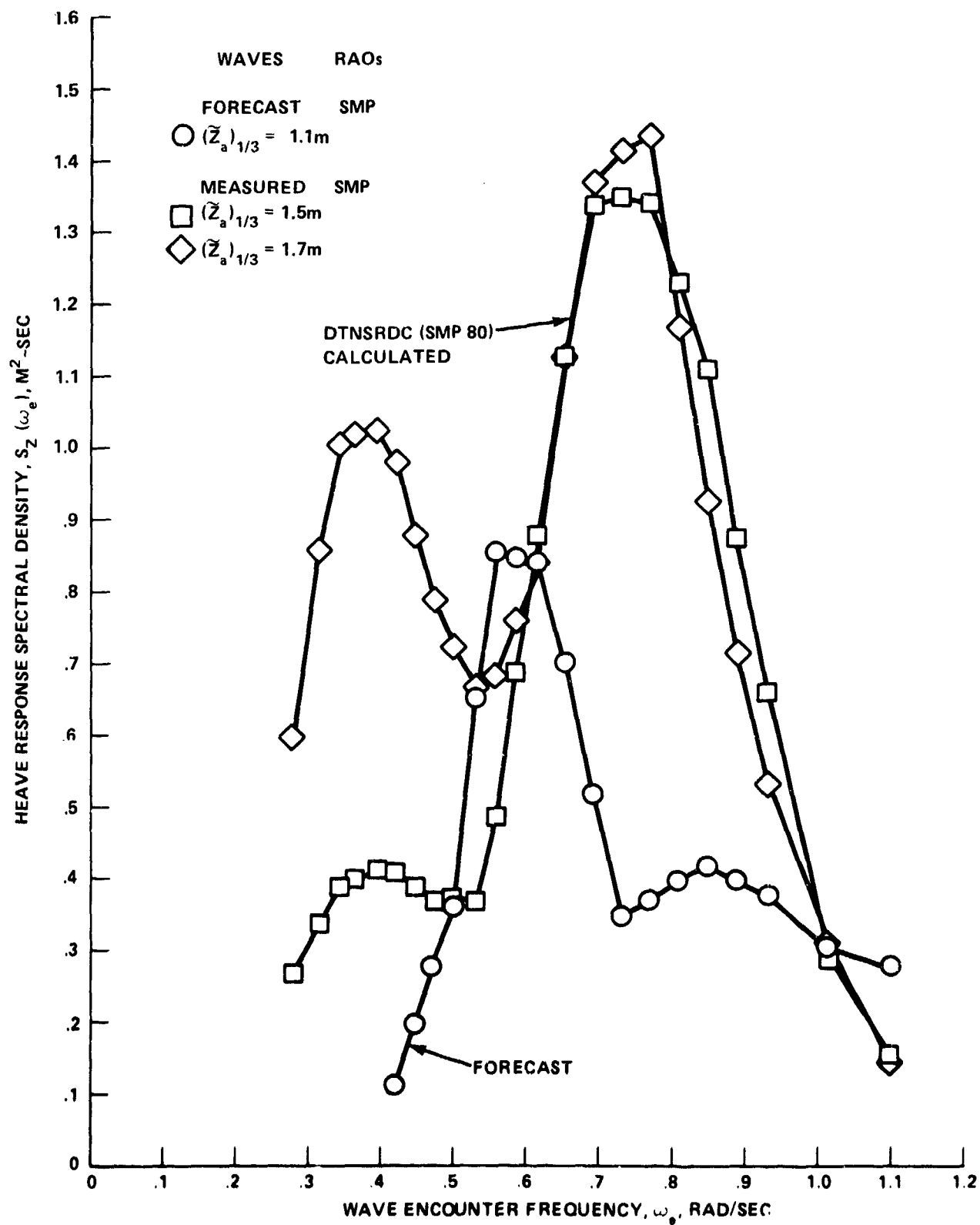


Figure 40 - TYDEMAN Heave Response In Head Seas with HOLLANDIA Spectra,
1 January 1979

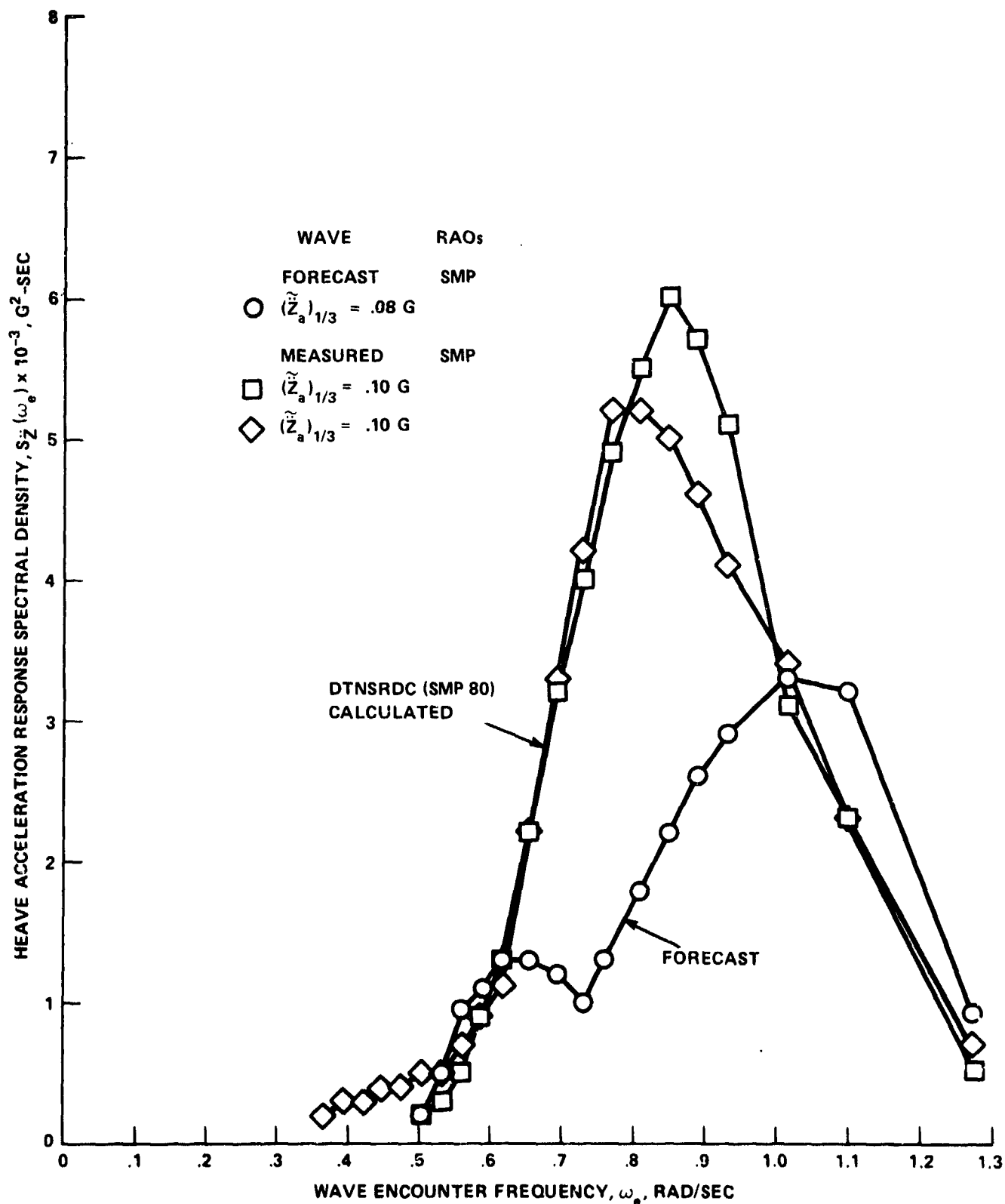


Figure 41 - TYDEMAN Heave Acceleration Response in Head Seas with HOLLANDIA Spectra, 1 January 1979

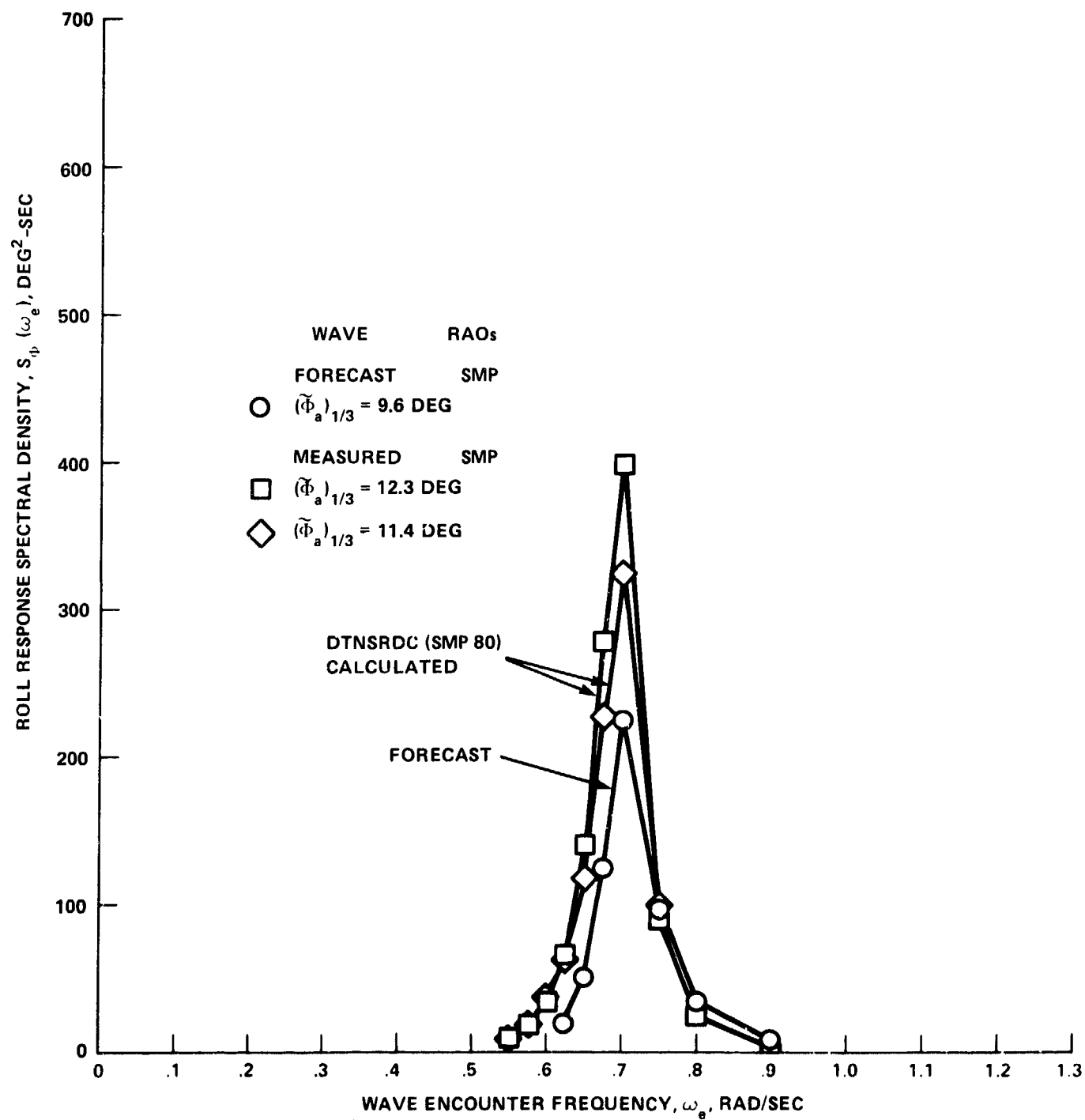


Figure 42 - TYDEMAN Roll Response in Beam Seas with HOLLANDIA Spectra, 1 January 1979

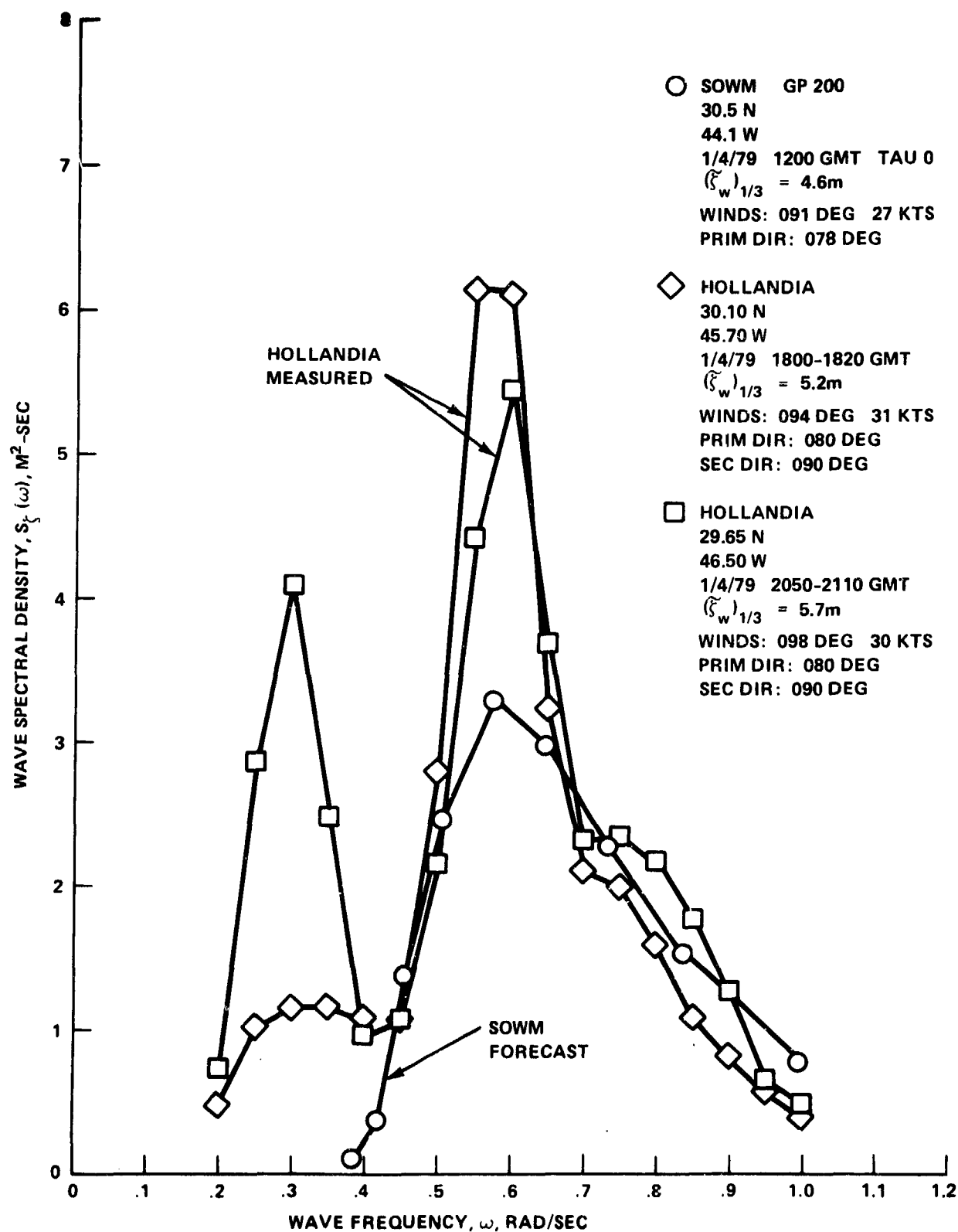


Figure 43 - Comparison Wave Spectral Density, Measured and Forecast - HOLLANDIA Trials, 4 January 1979

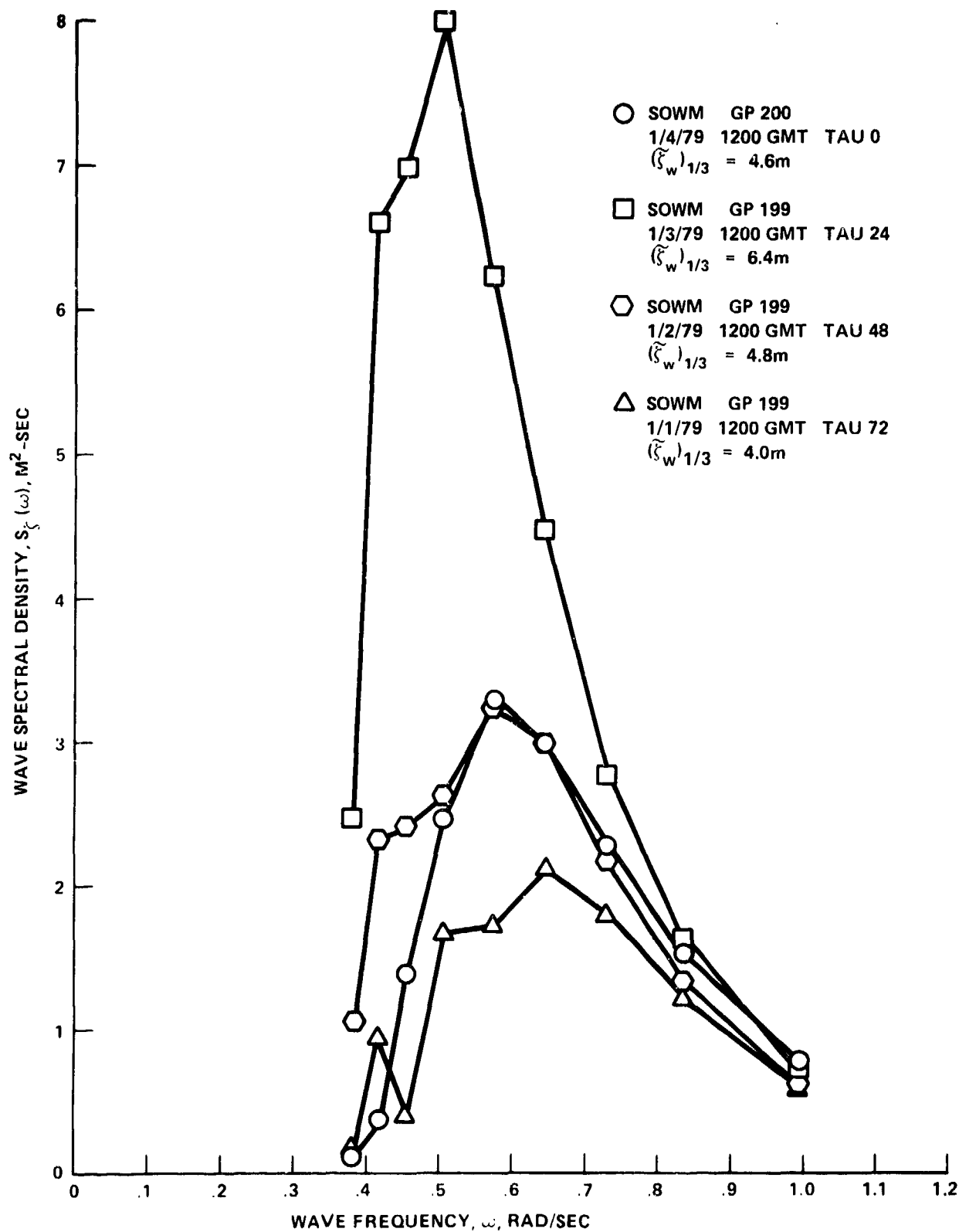


Figure 44 - Comparison of SOWM Forecasts Projected to the Same Day - HOLLANDIA Trials, 4 January 1979

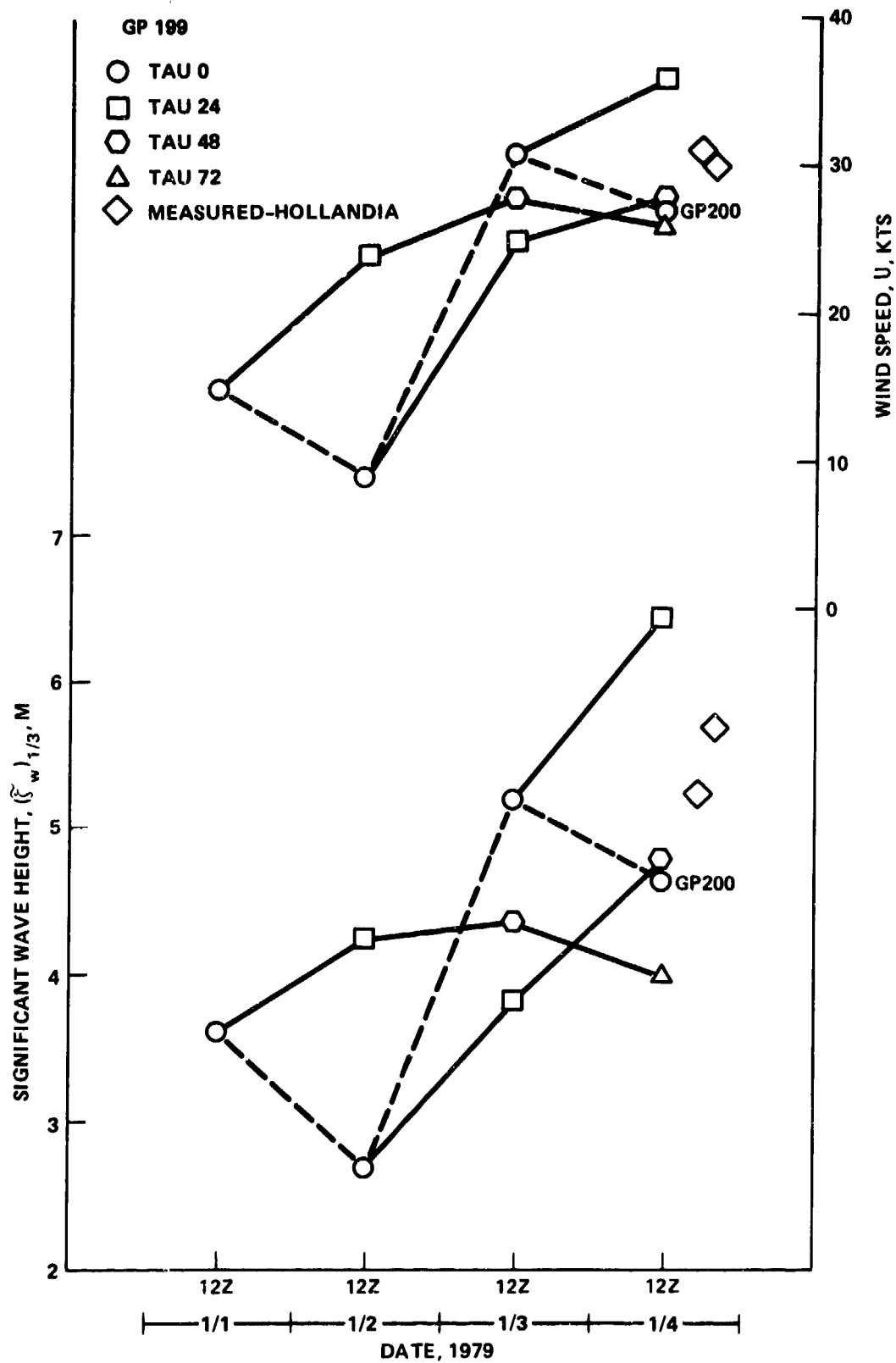


Figure 45 - Comparison of HOLLANDIA Measurements and SOWM Forecasts for Wind Speed and Significant Wave Height, GP 199

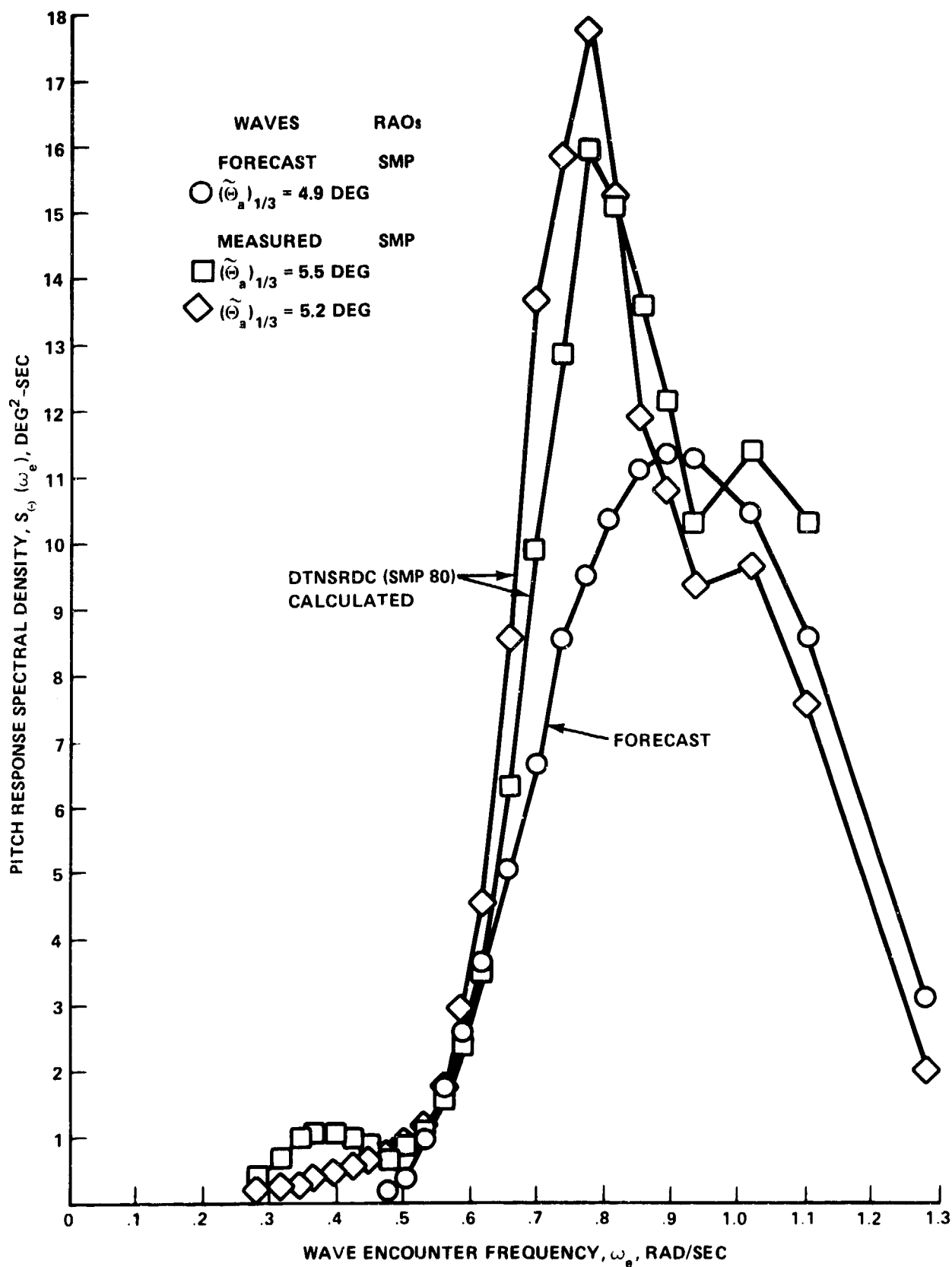


Figure 46 - TYDEMAN Pitch Response In Head Seas with HOLLANDIA Spectra, 4 January 1979

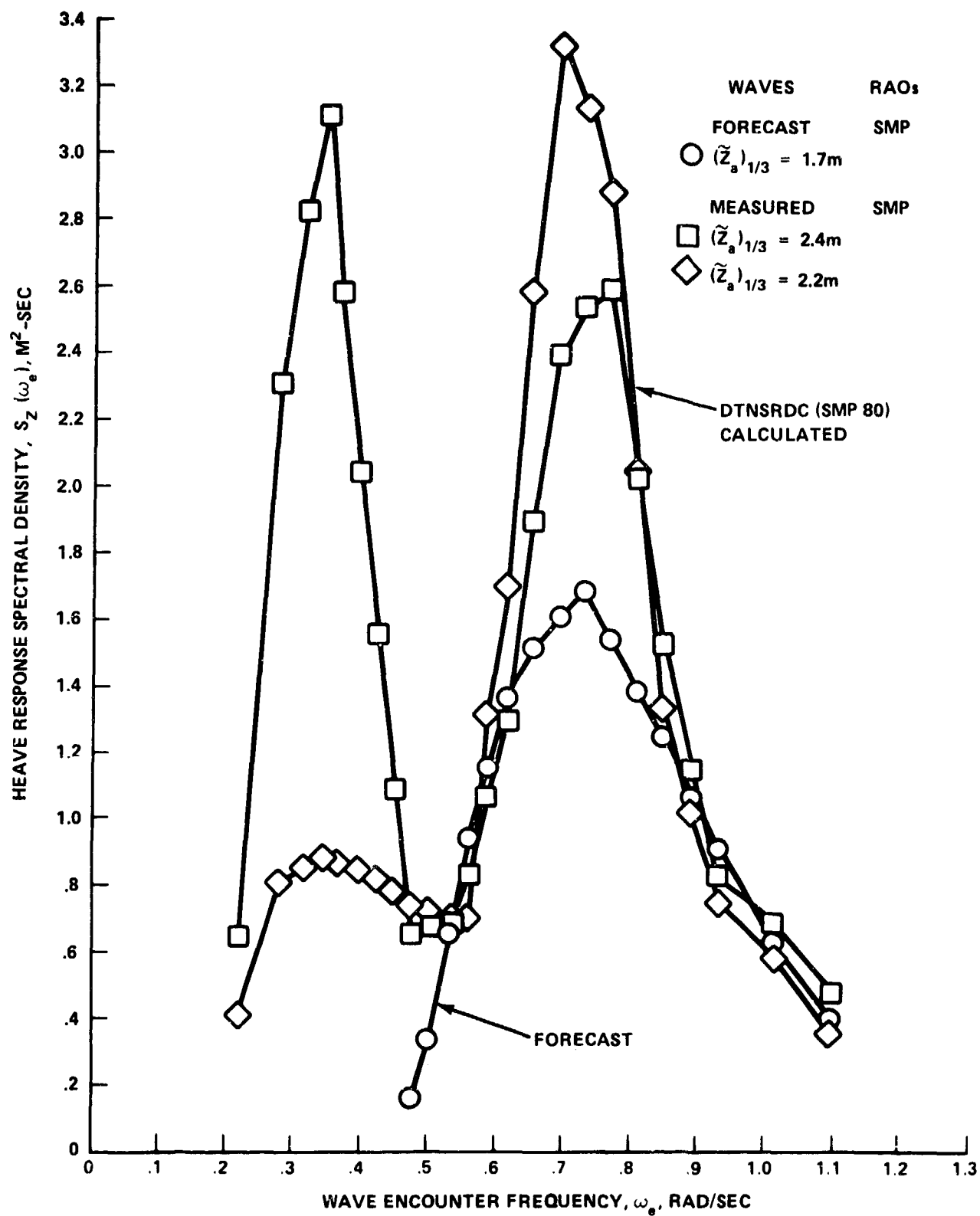


Figure 47 - TYDEMAN Heave Response in Head Seas with HOLLANDIA Spectra, 4 January 1979

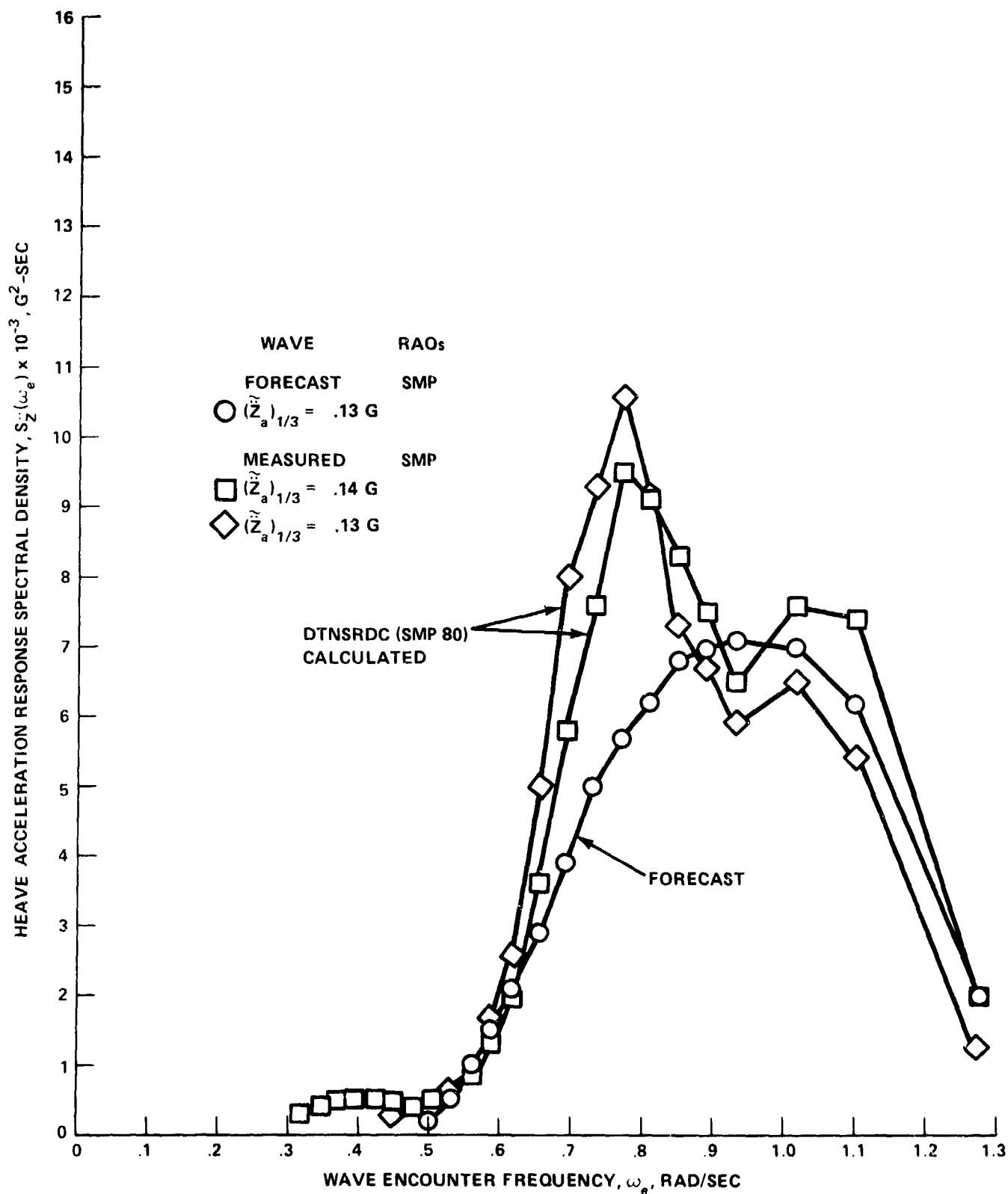


Figure 48 - TYDEMAN Heave Acceleration Response in Head Seas with HOLLANDIA Spectra, 4 January 1979

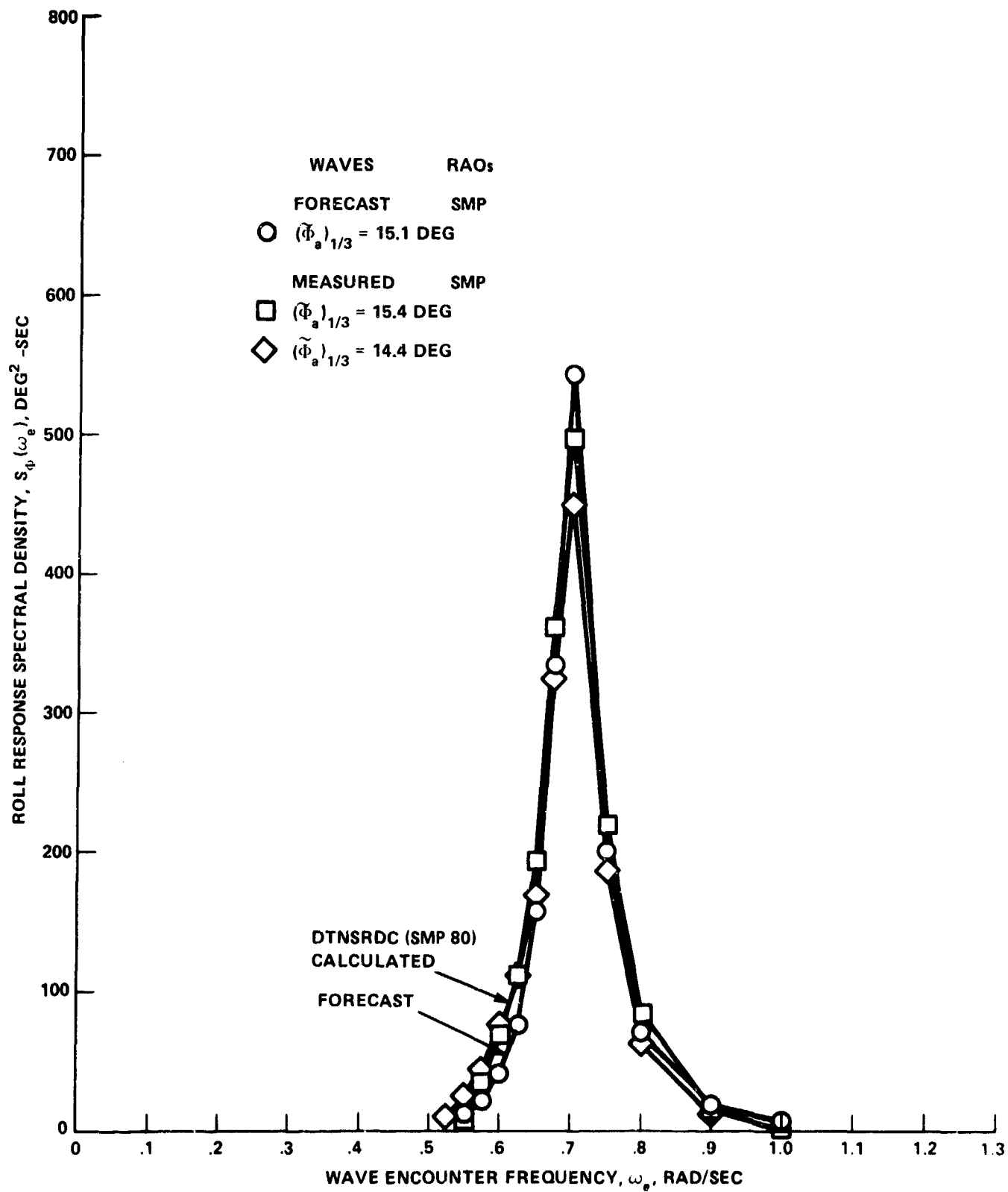


Figure 49 - TYDEMAN Roll Response in Beam Seas with HOLLANDIA Spectra,
4 January 1979

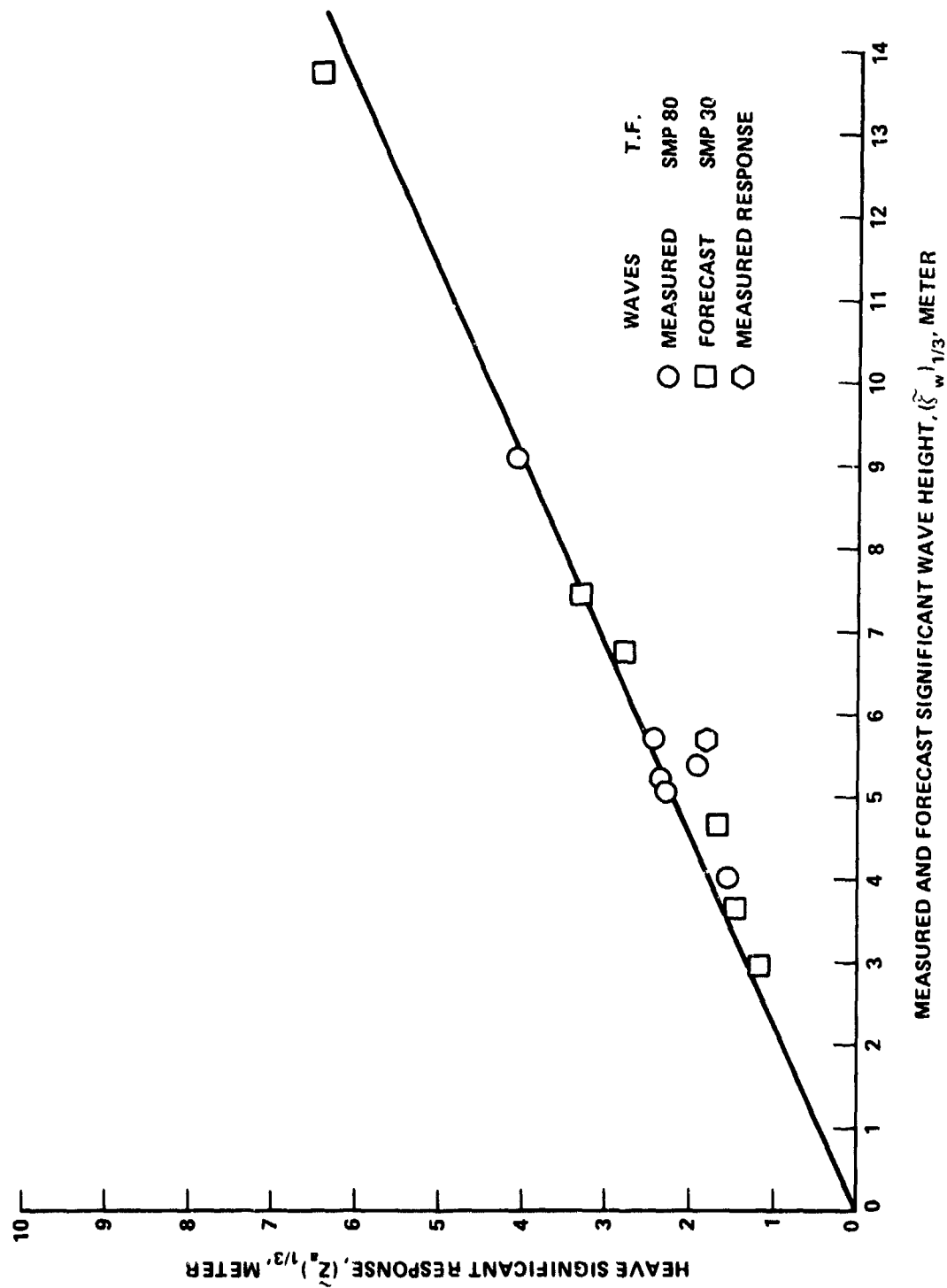


Figure 51 - Comparison of Heave Significant Response

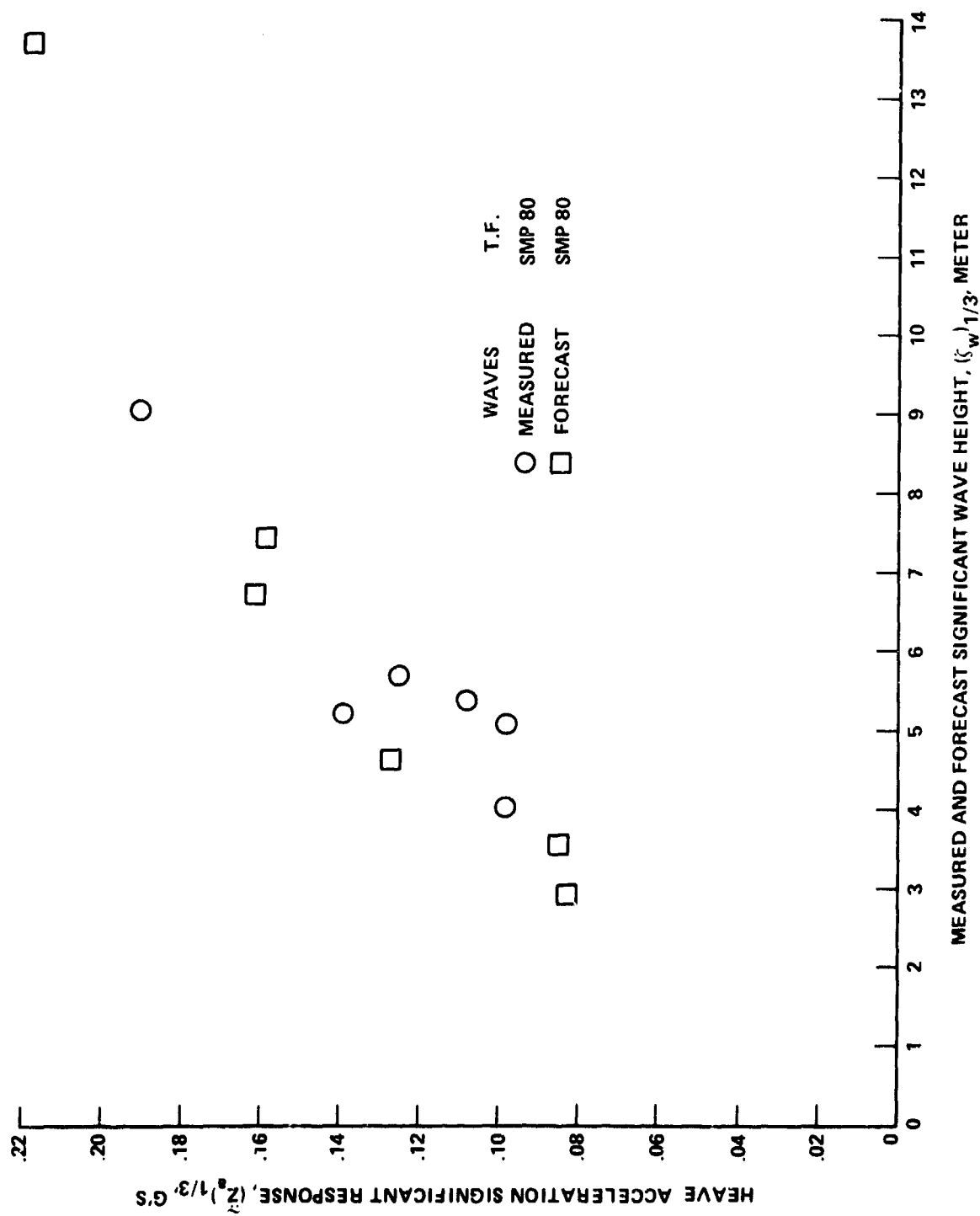


Figure 52 - Comparison of Heave Acceleration Significant Response

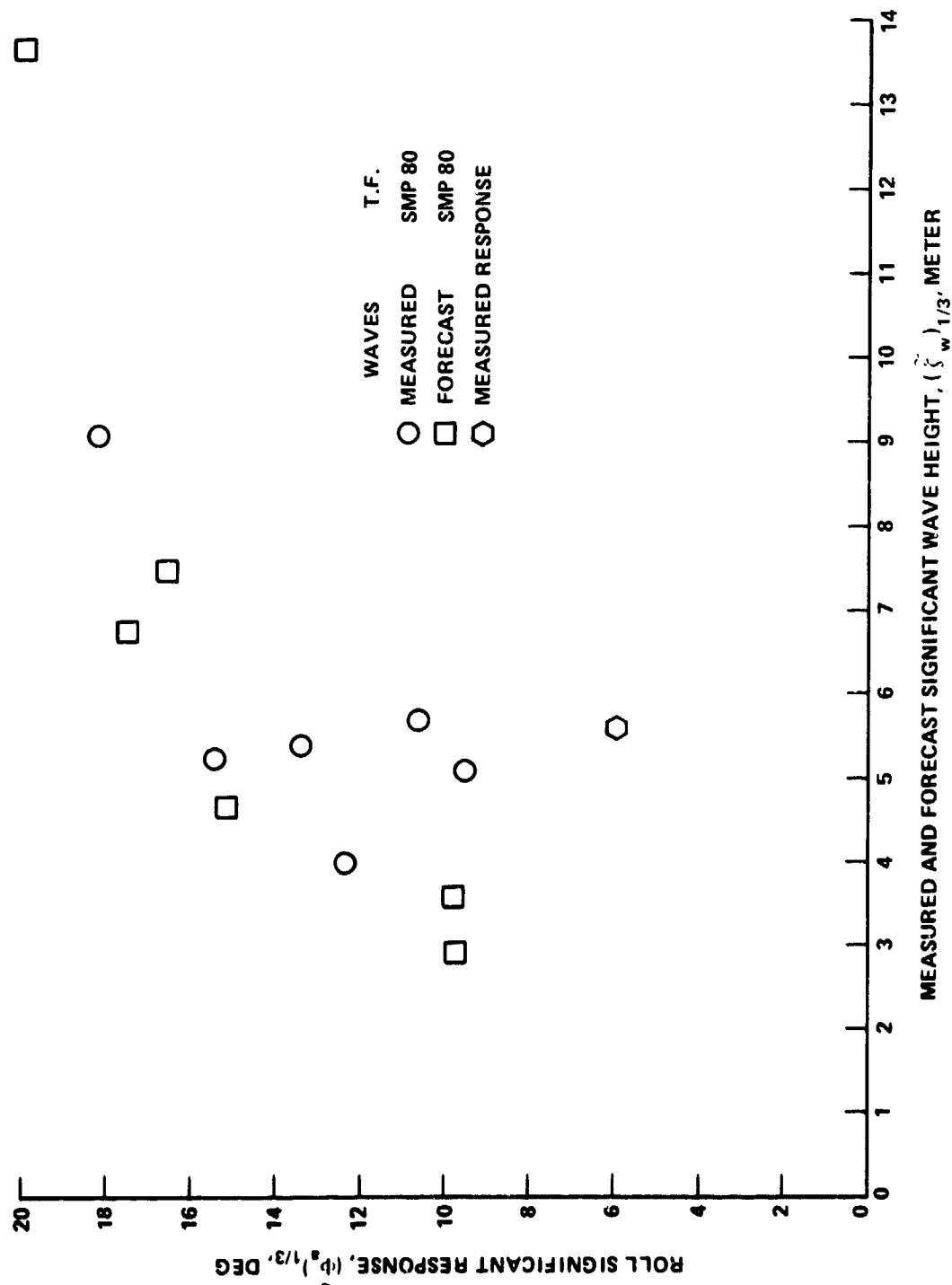


Figure 53 - Comparison of Roll Significant Response

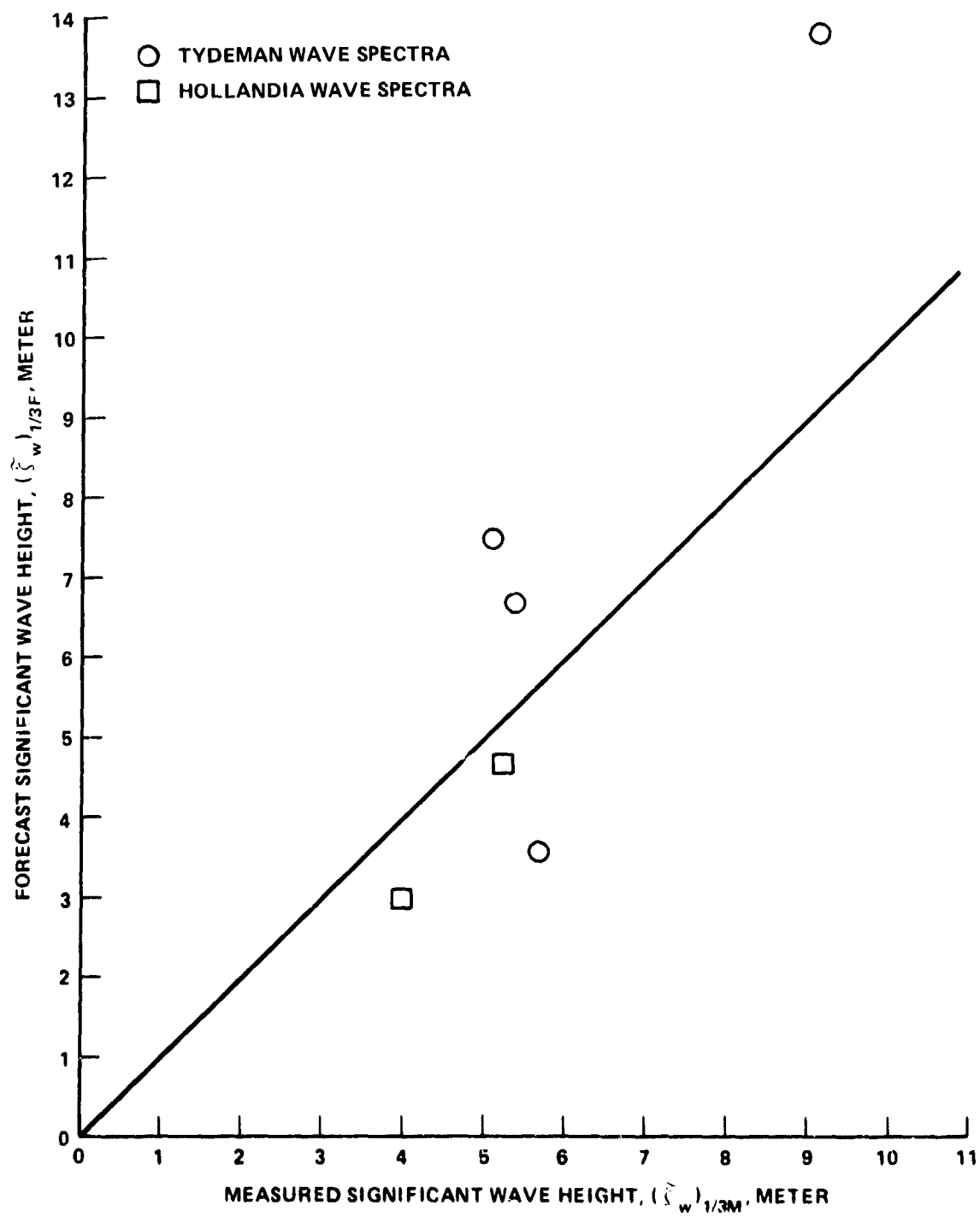


Figure 54 - Comparison of Measured and Forecast Wave Height

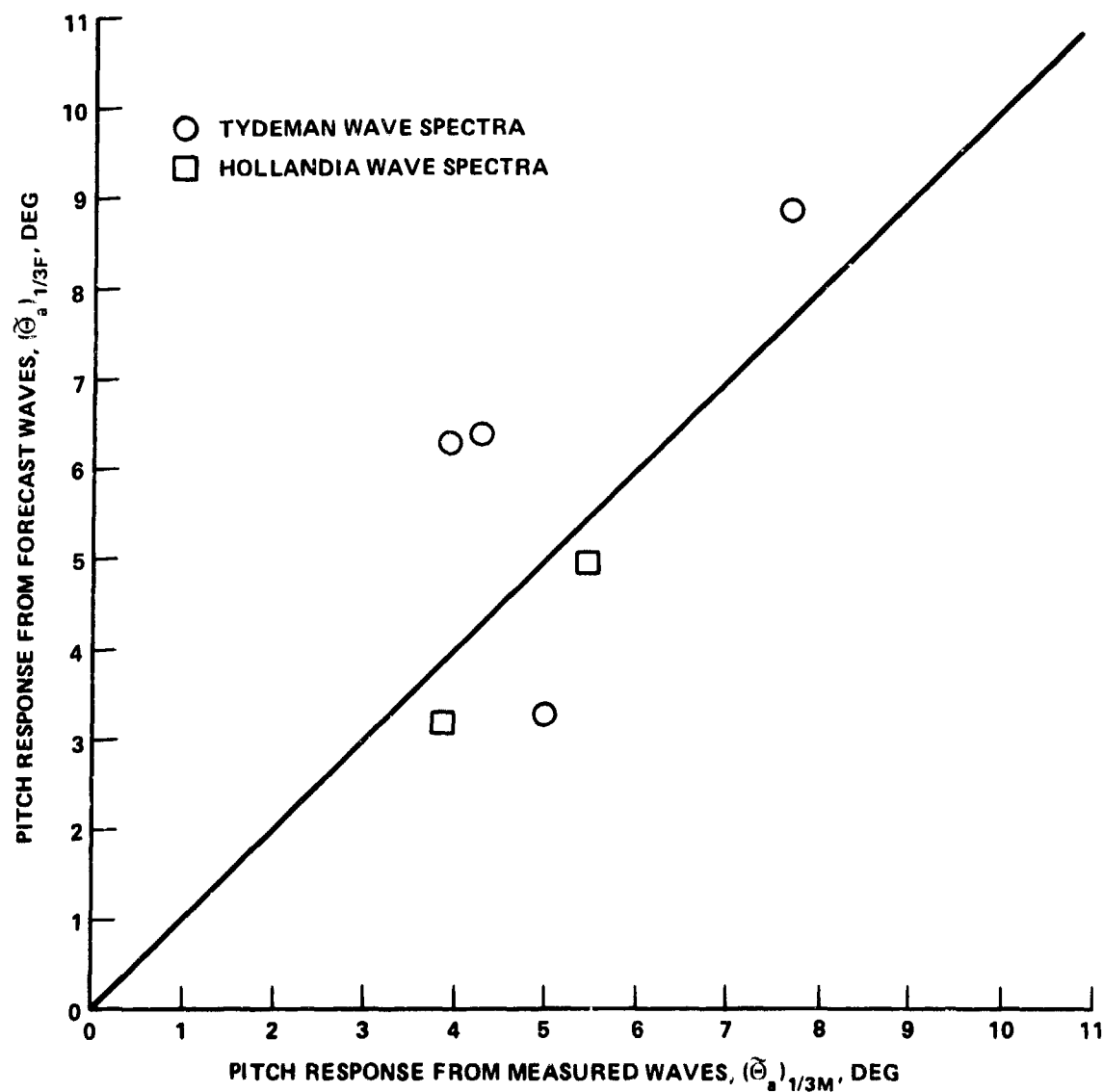


Figure 55 - Comparison of Pitch Response for Measured and Forecast Waves Developed with SMP80

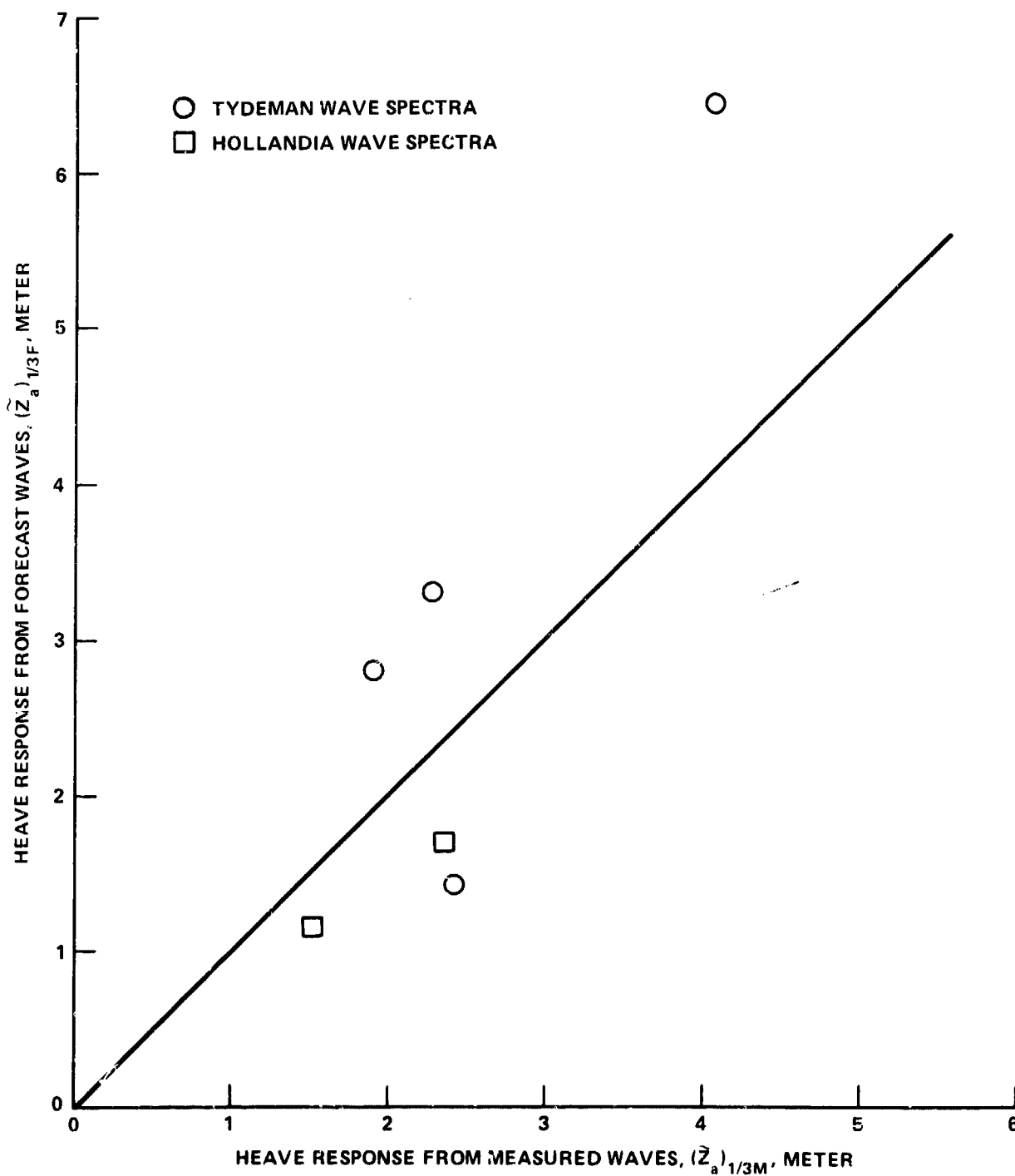


Figure 56 - Comparison of Heave Response for Measured and Forecast Waves Developed with SMP80

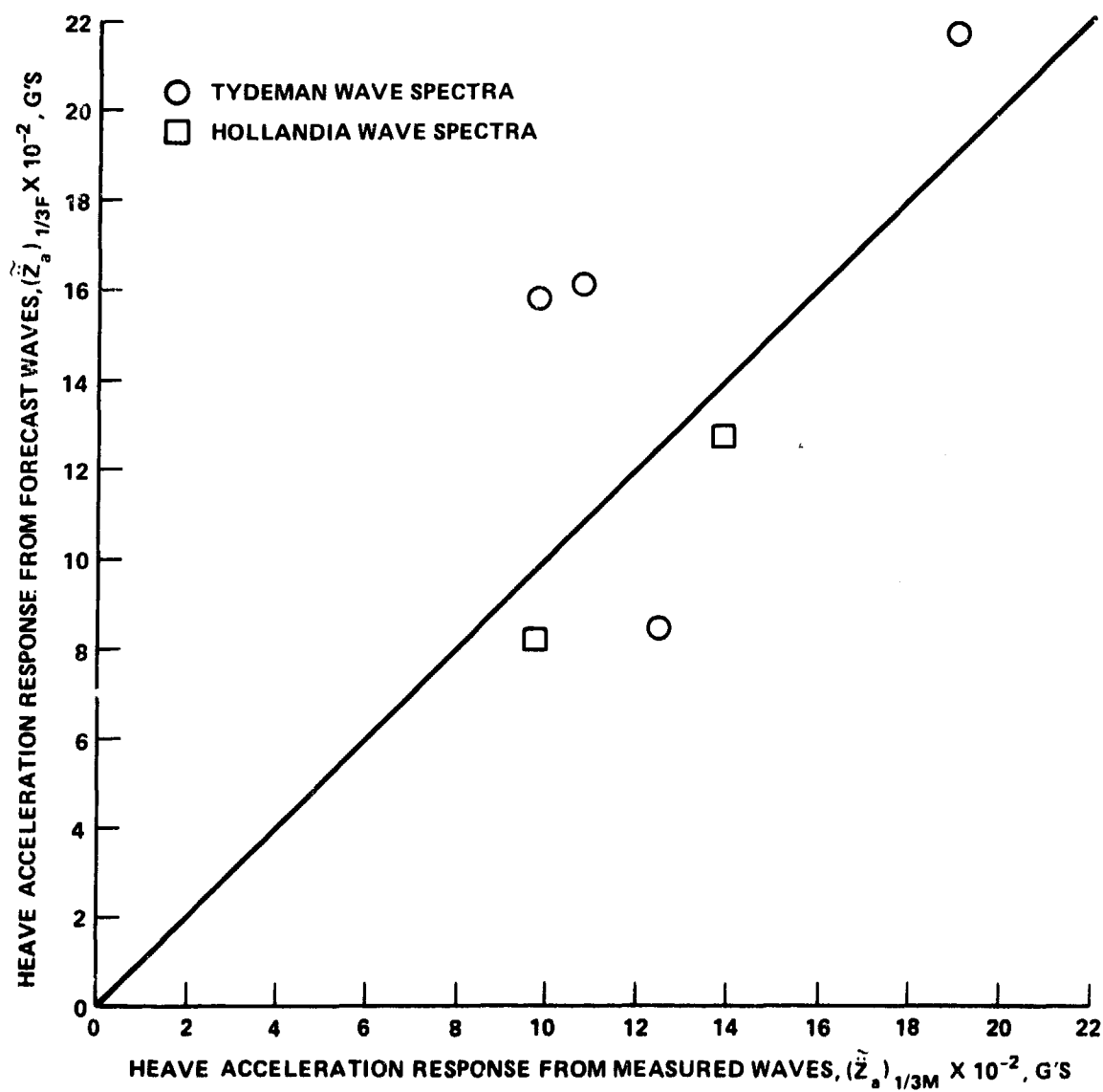


Figure 57 - Comparison of Heave Acceleration Response for Measured and Forecast Waves Developed with SMP80

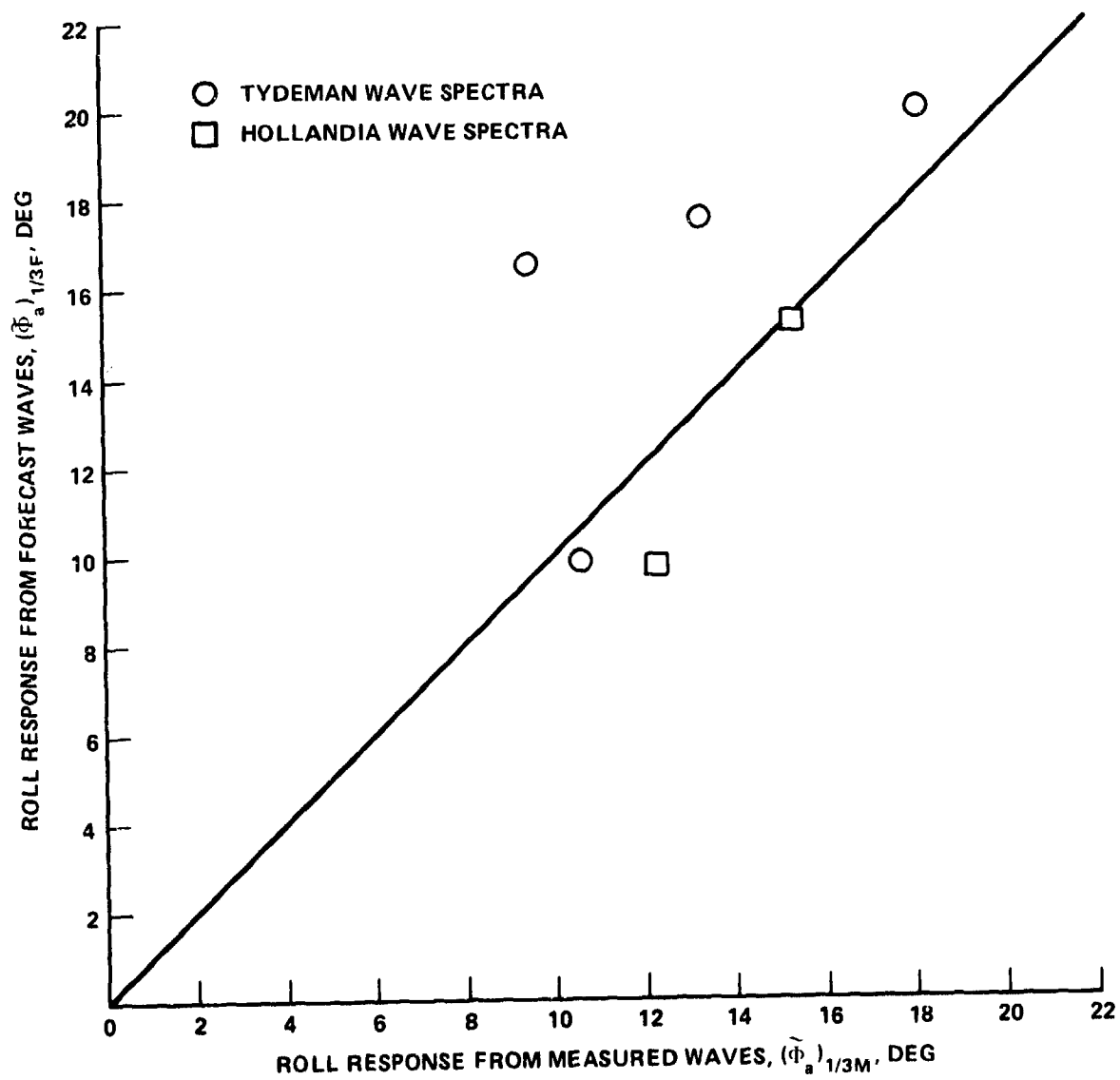


Figure 58 - Comparison of Roll Response for Measured and Forecast Waves Developed with SMP80

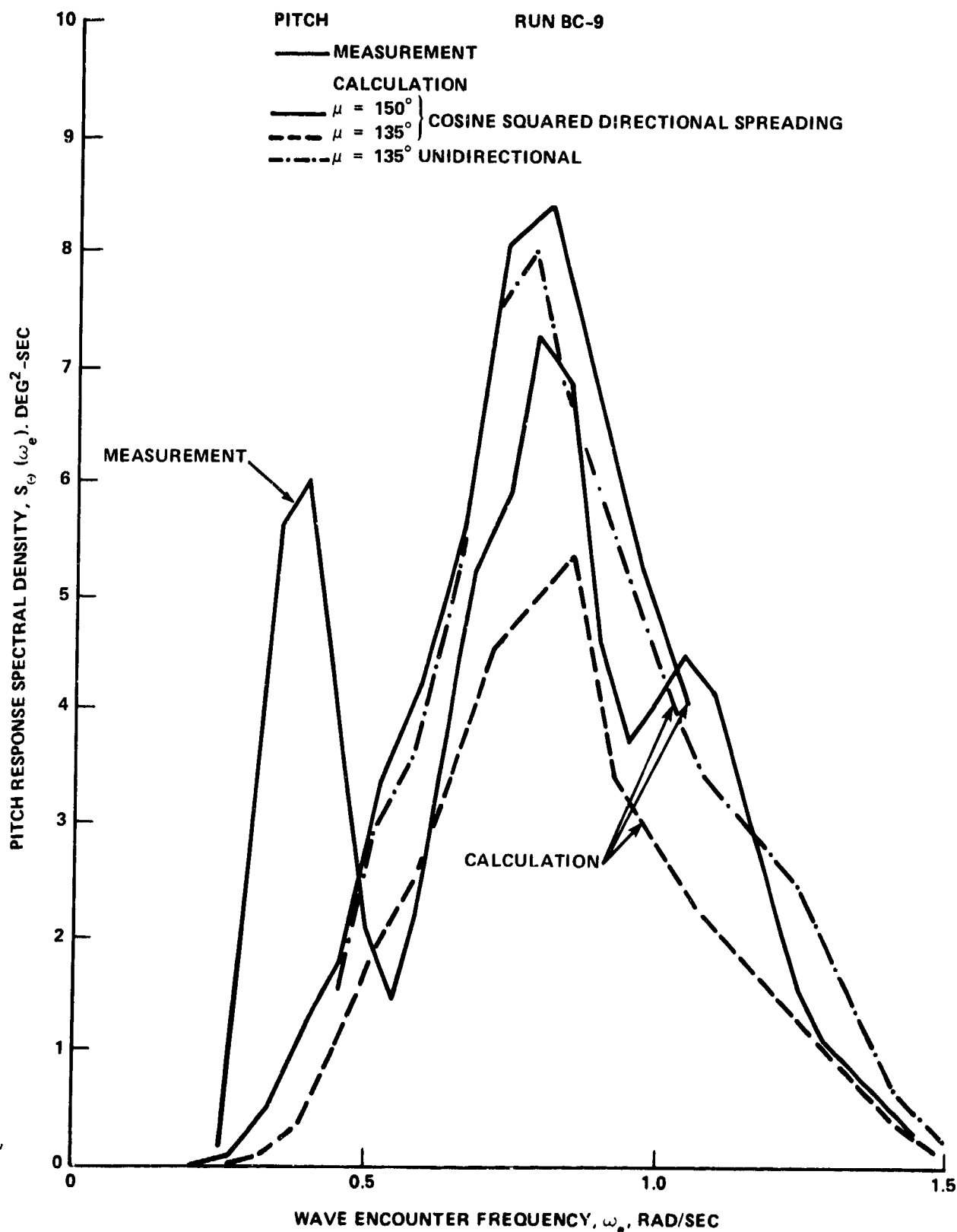


Figure 59 - Measured and Calculated Pitch Response Spectra for Different Main Directions with and without Cosine Squared Directional Spreading (Reference 7)

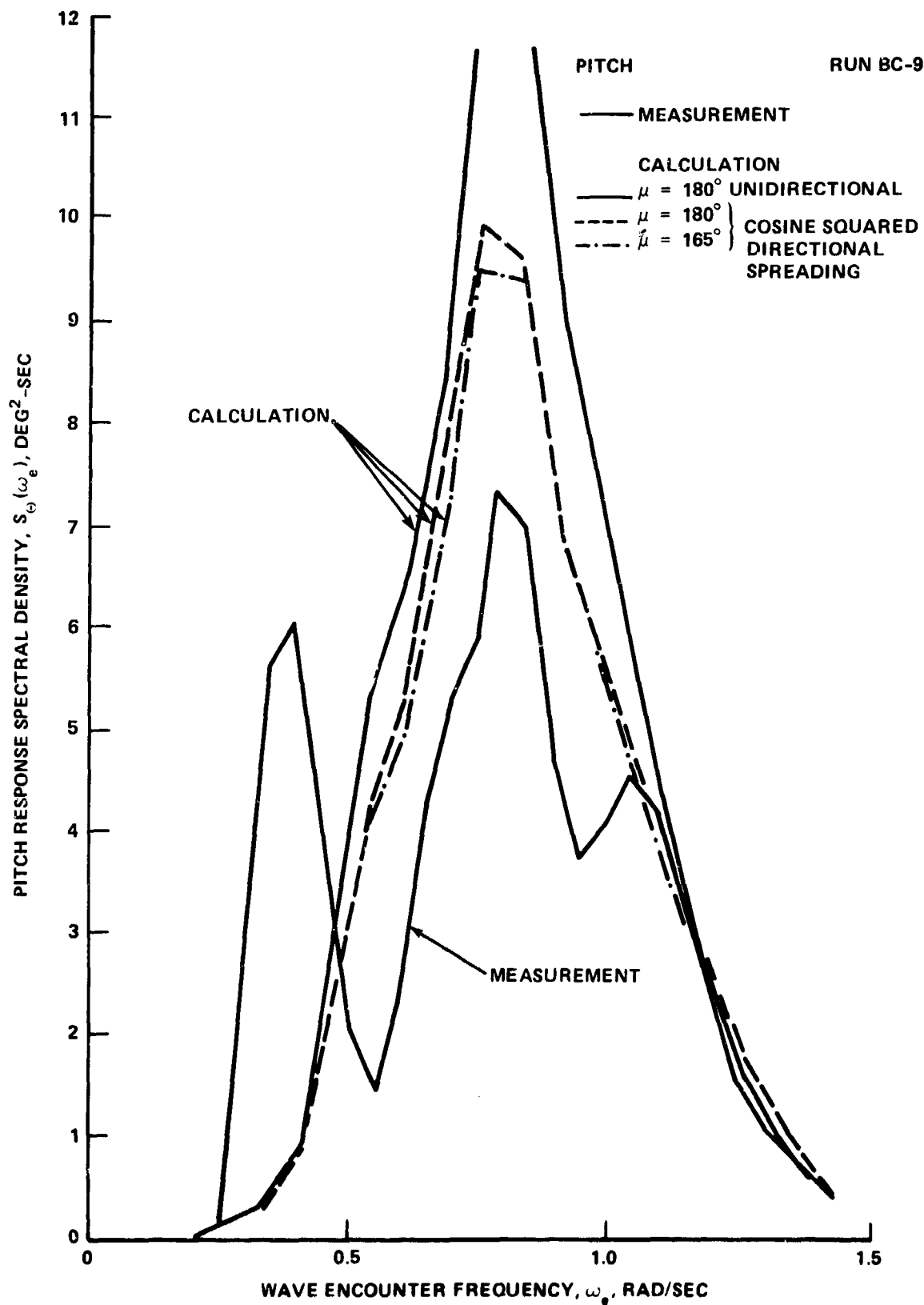


Figure 60 - Measured and Calculated Pitch Response Spectra for Different Main Directions with and without Cosine Squared Directional Spreading (Reference 7)

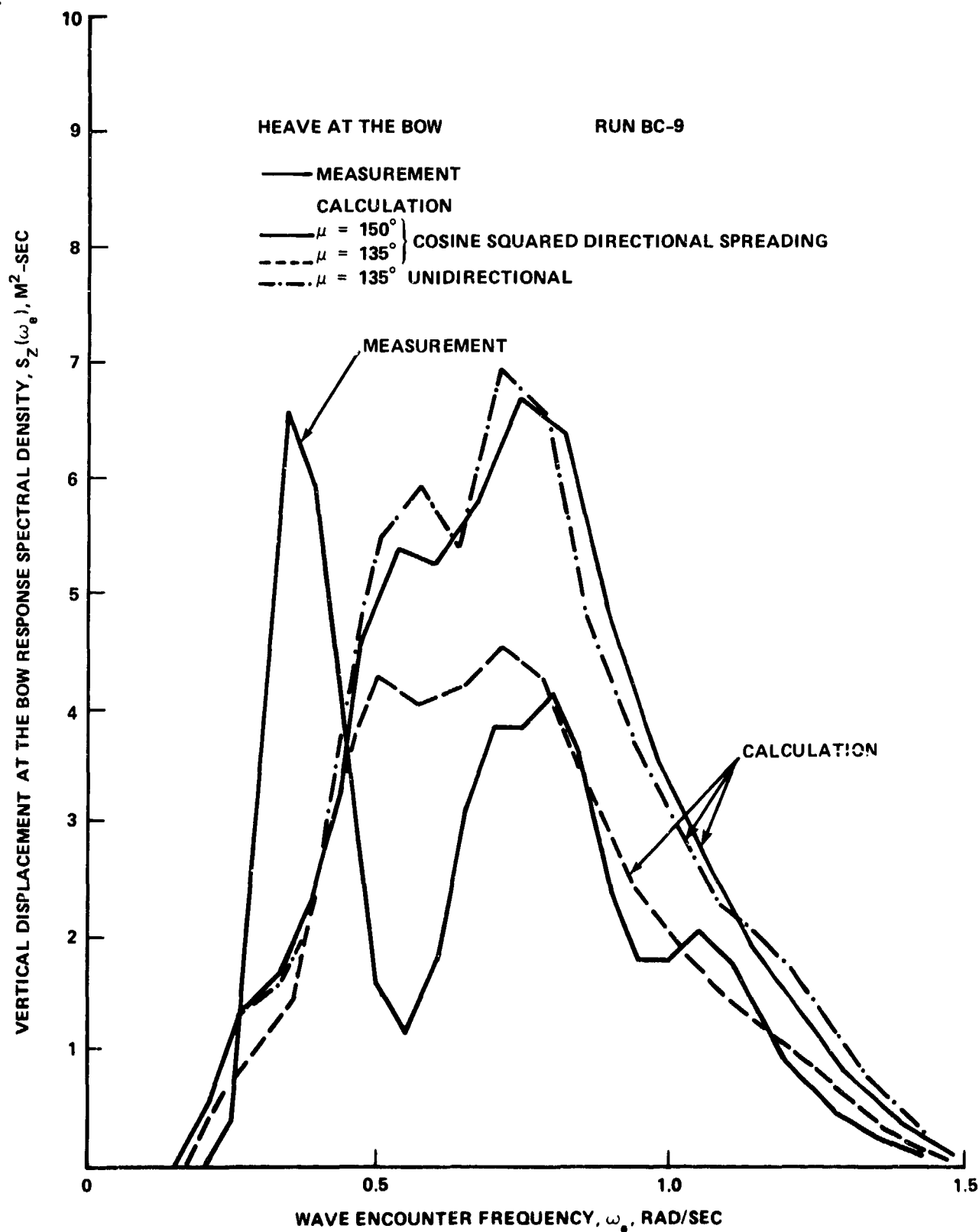


Figure 61 - Measured and Calculated Vertical Displacement at the Bow Response Spectra for Different Main Directions with and without Cosine Squared Directional Spreading (Reference 7)

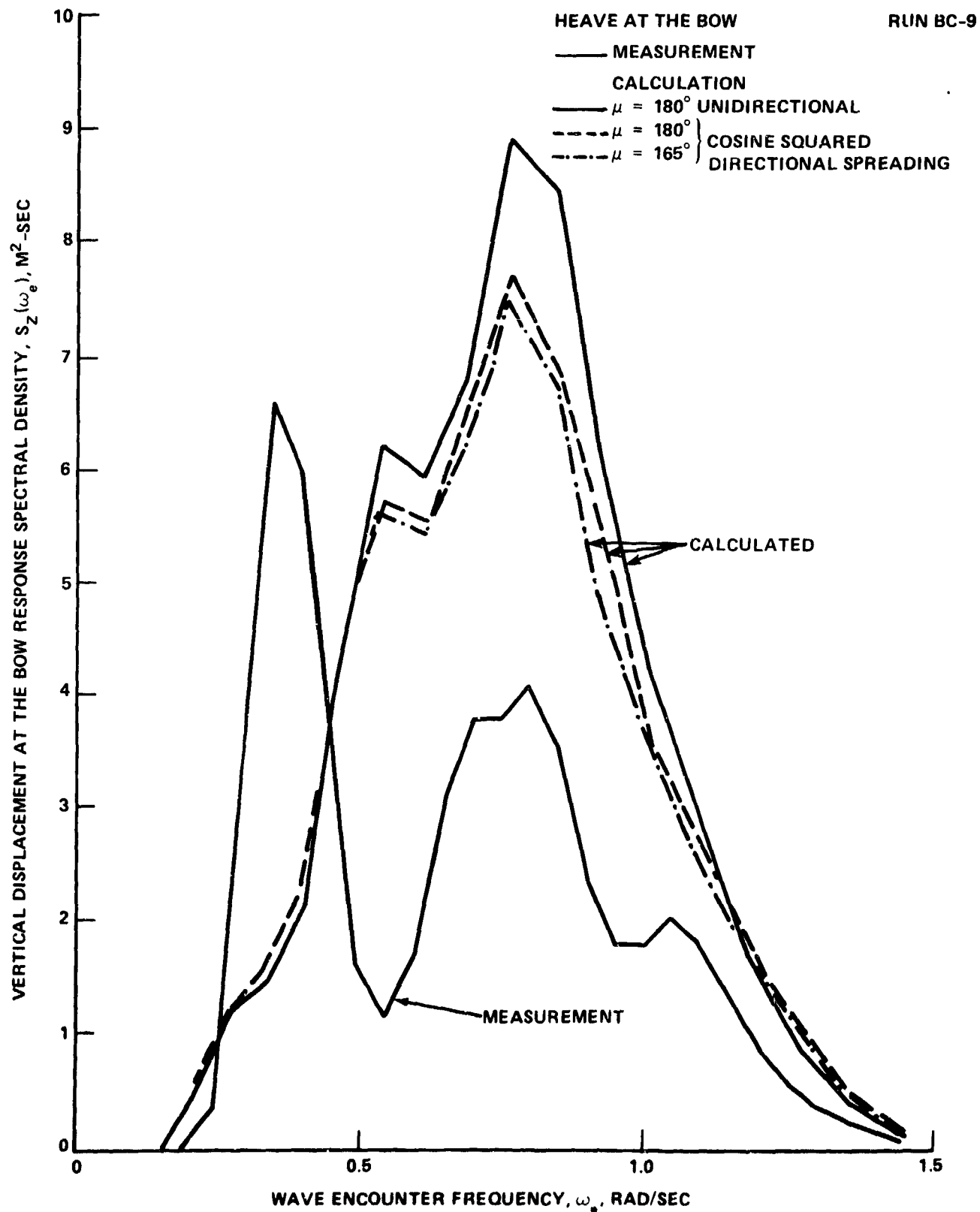


Figure 62 - Measured and Calculated Vertical Displacement at the Bow Response Spectra for Different Main Directions with and without Cosine Squared Directional Spreading (Reference 7)

TABLE 1 - PRINCIPAL DIMENSIONS, HNLMS TYDEMAN

Length Overall	(approximately) 90.15 m
Length between Perpendiculars	84.50 m
Beam, Moulded	14.40 m
Draft Forward	4.38 m
Draft Aft	4.92 m
Volume of Displacement in Seawater	2796 m ³
Longitudinal Radius of Inertia	21.1 m
Metacentric Height	1.157 m

TABLE 2 - MEASURED WAVE HEIGHT, WIND SPEED, WIND DIRECTION,
TYDEMAN TRIALS, 16 MARCH 1978

Date	GMT	Run	Symbol	Position	Significant Wave Height $(\bar{\zeta}_w)_{1/3}$ m	Wave Direction degrees	True Wind Speed m/s knots	True Wind Direction degrees
3/16/78	0815	BC 9	○	58°32'N 11°30'W	5.7	060	10.2 19.8	034
3/16/78	0900	DE 9	○	58°35'N 11°19'W	5.5	060	13.4 26.0	041
3/16/78	0945	FG 9	△	58°28'N 11°20'W	5.1	060	13.8 26.8	059
3/16/78	1100	HI 9	□	58°38'N 11°30'W	5.0	060	13.2 25.7	038
3/16/78	1200	CB 9	◇	58°34'N 11°20'W	4.9	060	11.3 22.0	050
3/16/78	1330	KJ 9	▷	58°26'N 11°28'W	4.7	060	13.2 25.7	053

TABLE 3 - 15 PERCENT ERROR BAND QUALIFICATION OF SIGNIFICANT VALUES
FOR MEASURED WAVES AND RESPONSE

Case	Measured	+15%	-15%	Forecast	Within	
					Yes	No
1:16 Mar 78	Waves Pitch Heave Vert. Disp. Bow Heave Accel. Roll	5.7/4.7 m 5.0 deg 2.4 m 4.8 m .13 G 10.6 deg	6.6/5.4 5.8 2.8 5.5 .15 12.2	4.8/4.0 4.3 2.0 4.1 .11 9.0	3.6 m 3.3 deg 1.4 m 3.1 m .08 G 9.8 deg	x x x x x x
2:8 Dec 78	Waves Pitch Heave Vert. Disp. Bow Heave Accel. Roll	7.3/5.1 m 3.9/4.5 deg 2.3/3.4 m 4.0 m .10/.11 G 9.5/10.9 deg	8.4/5.9 4.5/5.2 2.7/3.9 4.6 .12/.13 10.9/12.5	6.2/4.3 3.3/3.8 2.0/2.9 3.4 .09/.09 8.1/9.3	7.5 m 6.3 deg 3.3 m 6.2 m .16 G 16.6 deg	x x x x x x
3:10 Dec 78	Waves Pitch Heave Heave Accel. Roll	6.2/5.4 m 4.3/5.3 deg 1.9/2.7 m .11/.13 G 13.4/15.7 deg	7.1/6.2 5.0/6.1 2.2/3.1 .13/.15 15.4/18.1	5.3/4.6 3.7/4.5 1.6/2.3 .09/.11 11.4/13.4	6.6 m 6.4 deg 2.8 m .16 G 17.5 deg	x x x x x
4:12 Dec 78	Waves Pitch Heave Heave Accel. Roll	9.1 m 7.7 deg 4.1 m .19 G 18.2 deg	10.5 8.9 4.7 .22 20.9	7.7 6.6 3.5 .16 15.5	13.8 m 8.9 deg 6.4 m .22 G 20.0 deg	x x x x x
5:1 Jan 79	Waves Pitch Heave Heave Accel. Roll	4.0/3.7 m 3.9/3.8 deg 1.5/1.7 m .10/.10 G 12.3/11.4 deg	4.6/4.3 4.5/4.4 1.7/2.0 .12/.12 15.2/13.1	3.4/3.2 3.3/3.2 1.3/1.5 .09/.09 10.5/9.7	2.9 m 3.2 deg 1.1 m .08 G 9.6 deg	x x x x x
6:4 Jan 79	Waves Pitch Heave Heave Accel. Roll	5.2/5.7 m 5.5/5.2 deg 2.4/2.2 m .14/.13 G 15.4/14.4 deg	6.0/6.6 6.3/6.0 2.8/2.5 .16/.15 17.7/16.6	4.4/4.9 4.7/4.4 2.0/1.9 .12/.11 13.1/12.2	4.7 m 4.9 deg 1.7 m .13 G 15.1 deg	x x x x x

TABLE 4 - INFLUENCE OF MAIN DIRECTION AND SPREADING OF WAVES
RUN BC9, V = 9 KNOTS

μ (deg)	$f(\mu) = \frac{2}{\pi} \cos^2 \mu$		$f(\mu) = 1$		Measurement	
	$(\tilde{z}_{Ba})_{1/3}$ (m)	$(\tilde{\theta}_a)_{1/3}$ (deg)	$(\tilde{z}_{Ba})_{1/3}$ (m)	$(\tilde{\theta}_a)_{1/3}$ (deg)	$(\tilde{z}_{Ba})_{1/3}$ (-)	$(\tilde{\theta}_a)_{1/3}$ (deg)
180	4.2	4.4	4.4	4.9	3.4	4.1
165	4.2	4.4	4.3	4.8	-	-
150	4.0	4.2	4.2	4.5	-	-
135	3.4	3.2	4.0	4.1	-	-

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